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Emissions of Greenhouse Gases in the United States 1997

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Preface

Title XVI, Section 1605(a) of the Energy Policy Act of 1992 (enacted October 24, 1992) provides:

> *Not later than one year after the date of the enactment of this Act, the Secretary, through the Energy Information Administration, shall develop, based on data available to, and obtained by, the Energy Information Administration, an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of the baseline period of 1987 through 1990. The Administrator of the Energy Information Administration shall annually update and analyze such inventory using available data. This subsection does not provide any new data collection authority.*

The first report in this series, *Emissions of Greenhouse Gases 1985-1990*, was published in September 1993. This report—the sixth annual report, as required by law—presents the Energy Information Administration's latest estimates of emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases.

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Introduction

Total U.S. emissions of greenhouse gases in 1997 increased by 1.4 percent from their 1996 level. Overall, U.S. emissions are now about 10 percent higher than they were in 1990. The expansion in 1997 is a return to earlier trends after the unusual growth in 1996 emissions (up by a revised 2.8 percent from the 1995 level),[1] which was caused primarily by severe weather in 1996 (see Table ES1). Since 1990, U.S. emissions have increased at a compounded annual rate of about 1.3 percent, slightly faster than population (1.1 percent) but more slowly than energy consumption (1.7 percent), electricity consumption (2.0 percent), or gross domestic product (GDP) (2.3 percent).

Table ES1 shows trends in emissions of the principal greenhouse gases, measured in million metric tons of gas. In Table ES2, the value shown for each gas is weighted by its global warming potential (GWP), which is a measure of "radiative forcing." This concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the impacts of different greenhouse gases on global warming, with the effect of carbon dioxide being equal to 1 (see "Units for Measuring Greenhouse Gases" on

Table ES1. Estimated U.S. Emissions of Greenhouse Gases by Gas, 1990-1997
(Million Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	P1997
Carbon Dioxide	4,971.7	4,916.3	4,988.8	5,109.8	5,183.9	5,236.4	5,422.3	5,503.0
Methane	30.2	30.4	30.4	29.7	29.9	30.0	29.1	29.1
Nitrous Oxide	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0
Halocarbons and Other Gases								
CFC-11, CFC-12, CFC-113 . .	0.2	0.2	0.1	0.1	0.1	0.1	0.1	*
HCFC-22	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF_6	*	*	*	*	*	*	*	*
Methyl Chloroform	0.2	0.2	0.1	0.1	0.1	*	*	*
Carbon Monoxide	87.4	89.2	86.2	86.3	90.3	81.3	80.4	NA
Nitrogen Oxides	21.6	21.5	21.9	22.2	22.5	21.7	21.3	NA
Nonmethane VOCs	18.9	19.1	18.7	18.9	19.5	18.6	17.2	NA

*Less than 50,000 metric tons of gas.

P = preliminary data. NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Sources: **Carbon dioxide, methane, nitrous oxide emissions:** EIA estimates described in Chapters 2, 3, and 4 of this report. **Halocarbons and other gases:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), p. ES-2, web site www.epa.gov/globalwarming/inventory/1998-inv.html. **Criteria pollutants:** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), Tables A-1–A-3, pp. A-2–A-18.

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[1] Last year's emissions increase has been revised downward on both absolute and percentage bases. EIA's estimate of the emissions increase between 1995 and 1996, originally 3.4 percent, has been revised to 2.8 percent. About one-quarter of the change results from a lower estimate of the increment in carbon dioxide emissions, based primarily on changes in coal consumption data for the electric utility sector. The other three-quarters of the revision results from the use of new methods to estimate methane and nitrous oxide emissions. The changes in estimation methods are discussed in detail in the body and related appendixes of this report.

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-1997
(Million Metric Tons of Carbon or Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	P1997
Carbon	1,356	1,341	1,361	1,394	1,414	1,428	1,479	1,501
Methane	173	174	174	170	171	172	167	167
Nitrous Oxide	82	83	85	86	91	88	86	85
HFCs, PFCs, and SF_6	22	22	23	23	26	31	35	38
Total	**1,633**	**1,620**	**1,643**	**1,673**	**1,702**	**1,719**	**1,767**	**1,791**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Sources: EIA estimates documented in this report.

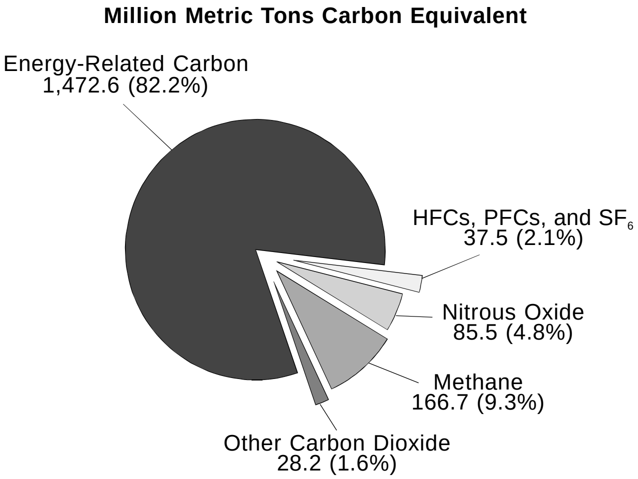
page 6).[2] The GWPs for other greenhouse gases are considerably higher (see discussion in Chapter 1).

Most (82 percent) of U.S. greenhouse gas emissions are caused by the combustion of fossil fuels such as coal, petroleum, and natural gas. Consequently, U.S. emissions trends are largely caused by trends in energy consumption. In recent years, national energy consumption, like emissions, has grown relatively slowly, with year-to-year fluctuations caused (in declining order of importance) by weather-related phenomena, business cycle fluctuations, and developments in domestic and international energy markets.

Other U.S. emissions include carbon dioxide from non-combustion sources (2 percent of total U.S. greenhouse gas emissions), methane (9 percent), nitrous oxide (5 percent), and other gases (2 percent) (Figure ES1). Methane and nitrous oxide emissions are caused by the biological decomposition of various waste streams, fugitive emissions from chemical processes, fossil fuel production and combustion, and many smaller sources. The other gases include hydrofluorocarbons (HFCs), used primarily as refrigerants, perfluorocarbons (PFCs), released as fugitive emissions from aluminum smelting and also used in semiconductor manufacture, and sulfur hexafluoride, used as an insulator in utility-scale electrical equipment.

The Kyoto Protocol, drafted in December 1997, raised the public profile of climate change issues in the United States in general, and of emissions estimates in particular. Emissions inventories are the yardstick by which the success or failure in complying with the Kyoto Protocol would be measured. This report, required by section 1605(a) of the Energy Policy Act of 1992, provides estimates of U.S. emissions of greenhouse gases, as well as information on the methods used to develop the estimates.

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 1997



Source: EIA estimates documented in this report.

Carbon Dioxide

Carbon dioxide accounts for 84 percent of U.S. greenhouse gas emissions. Carbon dioxide emissions originate almost entirely from fossil energy consumption and are influenced by the interaction of three factors:

- Consumption of energy-using services, such as travel, space heating and cooling, and industrial processes such as metal smelting and cement manufacture
- The “energy intensity” of energy-using services—that is, the amount of energy used for each type of service

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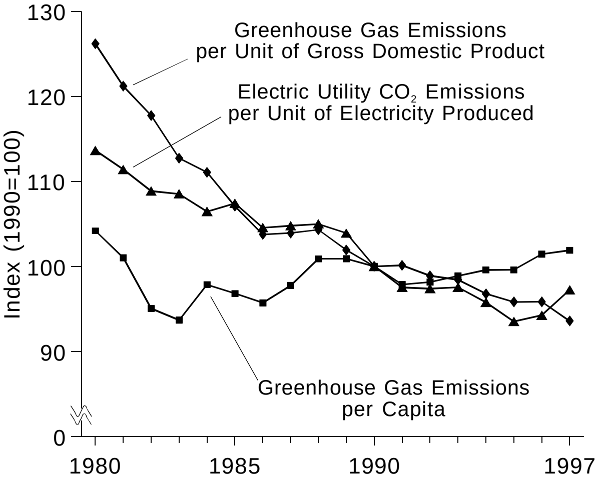
[2] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

- The "carbon intensity" of the energy sources—that is, the amount of carbon released per unit of energy used to provide the services, particularly, electricity.

Figure ES2 illustrates some recent U.S. trends in these areas. Emissions per dollar of GDP and emissions per capita are crude measures of the carbon intensity of the use of energy services. U.S. emissions per capita, which declined in the early 1980s, have risen in the 1990s, although at a relatively low rate. Emissions per dollar of GDP have declined almost every year. On the other hand, some of the indicators of carbon intensity have begun to increase, particularly, emissions per kilowatt-hour of electric power generation.

Figure ES2. Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1980-1997

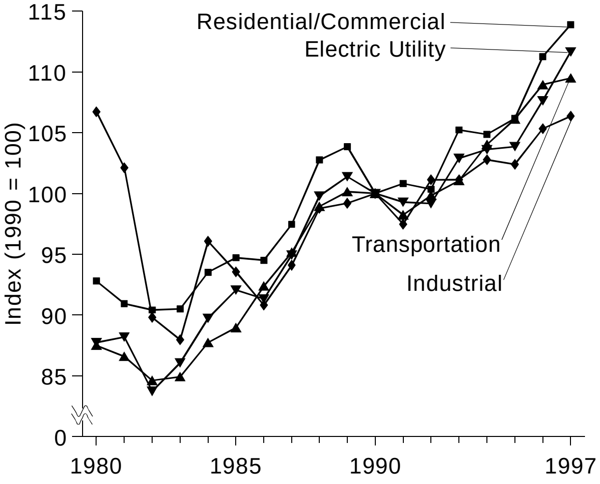


Sources: EIA estimates documented in this report.

During the early 1990s, several unrelated factors combined to lower the carbon intensity of power generation, including the expansion of natural-gas-fired generation caused by relatively low natural gas prices and better nuclear power plant operating rates. Over the past 2 years, however, the trends for some of those factors have reversed. Several nuclear power plants have been shut down since 1995, and nuclear generation declined by about 7 percent between 1996 and 1997; natural gas prices have risen, with the result that utilities have turned increasingly to existing coal plants for power generation.

Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. Emissions from the industrial sector dropped substantially in the early 1980s as higher energy prices induced industry to adopt energy-efficient technologies. Emissions from other sectors also dropped slightly in the early 1980s. In the late 1980s, however, emissions rose consistently as energy prices dropped dramatically and the economy grew. In 1990, somewhat higher energy prices induced an economic slowdown that was felt most strongly in 1991, with the result that emissions fell. Since 1991, emissions have grown consistently in all sectors, with the largest increases in the transportation and electric power sectors. Emissions in the industrial sector have grown relatively slowly, even during a vigorous economic expansion, due to energy efficiency improvements and low growth in energy-intensive industries.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1980-1997



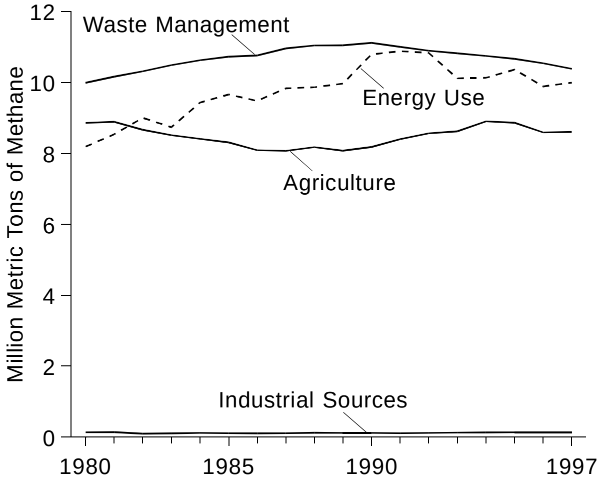
Source: EIA estimates documented in Chapter 2 of this report.

Methane

Methane accounts for about 9 percent of U.S. GWP-weighted greenhouse gas emissions. In contrast to carbon dioxide, there is no clear trend in methane emissions: they appear to have remained roughly constant through the 1990s, or perhaps to have declined slightly. Methane emissions estimates are more uncertain than those for carbon dioxide, however, and correspondingly less confidence can be placed in the apparent trends.

Methane emissions come from three categories of sources, each accounting for approximately one-third of U.S. methane emissions, or about 3 percent of the Nation's total greenhouse gas emissions. The largest of the three sources is the anaerobic decomposition of municipal solid waste in landfills (Figure ES4). Emissions from this source are declining (although very slowly) as a consequence of a reduction in the volume of waste landfilled and a gradual increase in the volumes of landfill gas captured for energy or flared. Methane is also emitted as a byproduct of fossil energy production and transport. Methane can leak from natural gas production and distribution systems and is also emitted as a consequence of coal production. Finally, domestic livestock management causes emissions from the animals and also from the anaerobic decomposition of their waste.

Figure ES4. U.S. Methane Emissions by Source, 1980-1997



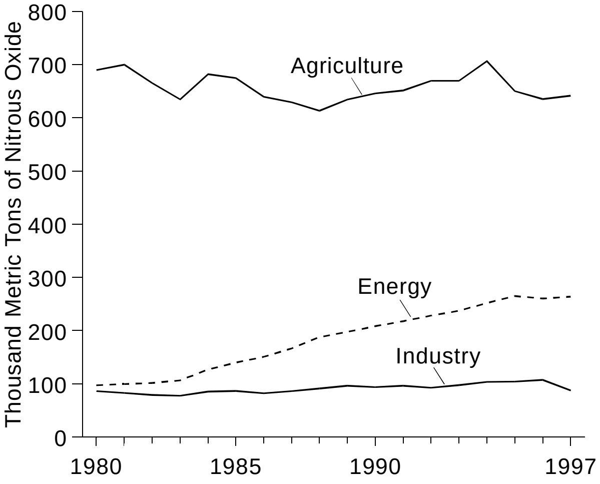
Source: EIA estimates documented in Chapter 3 of this report.

Nitrous Oxide

Nitrous oxide accounts for about 5 percent of U.S. GWP-weighted greenhouse gas emissions. Emissions estimates for nitrous oxide are more uncertain than those for either carbon dioxide or methane. The emissions estimate for nitrous oxide in this year's report is three times larger than the estimate last year, as a result of the implementation of the new IPCC methods for estimating nitrous oxide emissions. Estimated nitrous oxide emissions have been roughly constant in the 1990s, with no clear trend.

The revised estimates of nitrous oxide emissions include one large class of sources and two small classes (Figure ES5). Agriculture is the major source, and agricultural emissions are dominated by emissions from nitrogen fertilization of agricultural soils. The emissions factor for this source has been raised somewhat, but the bulk of the increase has been caused by the counting of nitrogen in manure used as fertilizer and nitrogen in crop residues, in addition to nitrogen from chemical fertilizers. Also, following the revised IPCC guidelines, secondary nitrous oxide emissions from nitrogen in agricultural runoff into streams and rivers have been incorporated. Motor vehicles equipped with catalytic converters also emit significant amounts of nitrous oxide. Certain chemical processes, fuel combustion, and wastewater treatment plants are smaller sources of nitrous oxide emissions.

Figure ES5. U.S. Nitrous Oxide Emissions by Source, 1980-1997



Source: EIA estimates documented in Chapter 4 of this report.

Halocarbons and Other Gases

The Kyoto Protocol specifies that emissions of several classes of engineered gases be limited: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Emissions of these three classes of gases account for about 2 percent of U.S. GWP-weighted emissions. There are several other categories of chemicals that also qualify as greenhouse gases but are excluded from the Framework Convention on Climate Change and the Kyoto Protocol because they are already controlled under the Montreal Protocol on Ozone-Depleting Substances. They include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and several solvents.

Emissions of the gases included in the Kyoto Protocol have increased rapidly in the 1990s, but emissions of all of them are very small (at most a few thousand metric tons). On the other hand, many of the gases have atmospheric lifetimes measured in the hundreds or thousands of years, and consequently they are potent greenhouse gases with global warming potentials hundreds or thousands of times higher than that of carbon dioxide per unit of molecular weight.

Land Use and Forestry

Forest lands in the United States are net absorbers of carbon dioxide from the atmosphere. According to U.S. Forest Service researchers, U.S. forest land absorbs about 200 million metric tons of carbon, equivalent to almost 15 percent of U.S. carbon dioxide emissions. Absorption is enabled by the reversal of the extensive deforestation of the United States that occurred in the late 19th and early 20th centuries. Since then, millions of acres of formerly cultivated land have been abandoned and have returned to forest. The regrowth of forests is sequestering carbon on a large scale. The process is steadily diminishing, however, because the rate at which forests absorb carbon slows as the trees mature.

The extent to which carbon sequestration should be included in emissions inventories generally, and the extent to which sequestration would “count” under the Kyoto Protocol, are still being determined. The Kyoto Protocol specifically limits “countable” effects for countries like the United States to anthropogenic afforestation, deforestation, and reforestation that has occurred “since 1990,” and only if it is “measurable and verifiable.” Each clause would probably limit the applicability of carbon sequestered as a result of land use changes and forestry.

1. U.S. Emissions of Greenhouse Gases in Perspective

About This Report

The Energy Information Administration (EIA) is required by the Energy Policy Act of 1992 to prepare a report on aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report is the sixth annual update, covering national emissions over the period 1990-1996, with preliminary estimates of emissions for 1997. The estimates contained in this report have been revised from those in last year's report (see "What's New in This Report," page 3). Emissions estimates for carbon dioxide are reported in metric tons of carbon; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," page 6) but can be converted to carbon equivalents using the factors provided in this report.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important recent developments in global climate change activities, especially the third Conference of the Parties to the Framework Convention on Climate Change, which was held in December 1997 in Kyoto, Japan. Chapters 2 through 5 cover emissions of carbon dioxide, methane, nitrous oxide, halocarbons and related gases, respectively. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

Six appendixes are included with this report. Appendix A provides a detailed discussion of emissions sources, estimation methods, and data requirements and sources. Appendix B describes the derivation of the carbon emissions coefficients used for the inventory. Appendix C describes uncertainties in the emissions estimates. Appendix D describes known emissions sources omitted from the main report because they are not deemed to be "anthropogenic," or because of excessive uncertainty. Appendix E provides a historical time series of U.S. carbon emissions. Appendix F provides some convenient conversion factors.

The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth's surface is equal to the amount of energy reradiated back into space in the form of infrared radiation, and the temperature of the Earth's surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of the Earth's atmosphere. Many gases in the Earth's atmosphere absorb infrared radiation reradiated from the Earth's surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth's surface would be on the order of -19^{o} Celsius,

Table 1. Global Atmospheric Concentrations of Selected Greenhouse Gases

Item	Carbon Dioxide	Methane	Nitrous Oxide	Sulfur Hexafluoride	Perfluoro-methane
	(parts per million)			(parts per trillion)	
Preindustrial Atmospheric Concentration	278	0.700	0.275	0	0
1992 Atmospheric Concentration	356	1.714	0.311	32	70
Average Annual Change, Recent Years	1.6	0.008	0.0008	0.2	1.2
Average Percent Change, Recent Years	0.4	0.6	0.25	0.6	1.7
Atmospheric Lifetime (Years)	50–200	12	120	3,200	50,000

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 92-93.

rather than the +15° Celsius actually observed.[1] The gases that help trap the Sun's heat close to the Earth's surface are referred to as "greenhouse gases." All greenhouse gases absorb infrared radiation (heat) at particular wavelengths.

The most important greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a host of engineered chemicals, such as hydrofluorocarbons (HFCs). Most greenhouse gases occur naturally. Water vapor is by far the most common, with an atmospheric concentration of nearly 1 percent, compared with less than 0.04 percent for carbon dioxide. Concentrations of other greenhouse gases are a fraction of that for carbon dioxide (Table 1).

Scientists recognized in the early 1960s that concentrations of carbon dioxide in the Earth's atmosphere were increasing every year. Subsequently, they discovered that atmospheric concentrations of methane, nitrous oxide, and many engineered chemicals also were rising. Because current concentrations of greenhouse gases keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

In computer-based simulation models, rising concentrations of greenhouse gases nearly always produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather and in the level of the oceans that might prove disruptive to current patterns of land use and human settlement, as well as to existing ecosystems. To date, it has proved difficult to detect firm evidence of actual temperature changes, in part because the normal temporal and spatial variations in temperature are far larger than the predicted change in the global average temperature. Even when temperature changes are identified, it is not possible to be certain whether they are random fluctuations that will reverse themselves or the beginning of a trend. The possible effects of rising temperatures on weather patterns are even more uncertain.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC), an international assemblage of scientists commissioned by the United Nations to study this matter, concluded that:

> *Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitudes and patterns of long-term variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernable human influence on global climate.*[2]

While both the existence and consequences of human-induced global climate change remain uncertain, the threat of climate change has put in train an array of efforts by the United States and other governments to find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused on identifying levels and sources of emissions of greenhouse gases and on possible mechanisms for reducing emissions or increasing absorption of greenhouse gases.

Global Sources of Greenhouse Gases

Most greenhouse gases have substantial natural sources in addition to human-made sources, and there are powerful natural mechanisms for removing them from the atmosphere. However, the continuing growth in atmospheric concentrations establishes that, for each of the major greenhouse gases, more gas is being emitted than is being absorbed each year: that is, the natural absorption mechanisms are lagging behind. Table 2

Table 2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases, 1992

Gas	Sources		Absorption	Annual Increase in Gas in the Atmosphere
	Natural	Human-Made		
Carbon Dioxide (Million Metric Tons of Carbon) . .	150,000	7,100	154,000	3,100–3,500
Methane (Million Metric Tons of Gas)	110–210	300–450	460–660	35–40
Nitrous Oxide (Million Metric Tons of Gas)	6–12	4–8	10–17	3–5

Source: Summarized from ranges appearing in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 17-19.

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[1] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 57. See also web site www.ipcc.ch.

[2] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 5.

What's New in This Report

- In keeping with current IPCC guidelines, carbon dioxide emissions from the consumption of bunker fuels (fuels used by ships and aircraft moving in international trade) have been subtracted from the estimates of energy-related carbon dioxide emissions.

- New IPCC emissions estimation methods for enhancement of nitrous oxide emissions from agricultural soils have more than doubled emissions from that source. The new methods attempt to capture emissions from the application of animal manure and crop residues to agricultural soils, as well as secondary emissions from nitrogen enhancement of water courses downstream from agricultural plots.

- This report incorporates revised emissions coefficients (developed by the U.S. Environmental Protection Agency's Office of Mobile Sources and released in August 1998) for nitrous oxide emissions from automobiles equipped with catalytic converters. Estimated emissions from this source are consequently somewhat higher than reported last year.

- New nitrous oxide emissions sources include (1) human waste in municipal wastewater, (2) waste combustion, and (3) solid waste from domesticated animals.

- Some new methods of calculating methane emissions estimates are used. They include a more disaggregated treatment of emissions from oil and gas systems and operations, a reduction in the share of crops burned and in related emissions, new degasification and recovery data for coal mine emissions, and State-level data for domesticated livestock.

- Methane emissions from natural gas venting have been removed from the emissions estimate, based on an understanding that the data reported as "venting and flaring" in EIA's energy statistics probably reflect balancing items and nonhydrocarbon gases removed in natural gas treatment plants, as well as wellhead venting or flaring of methane. This matter remains under review.

- This report includes, for the first time, estimated emissions of the carbon dioxide extracted from natural gas production, which increases estimated emissions of greenhouse gases by 4 million metric tons of carbon, or less than 0.5 percent of total emissions.

- An Appendix E has been added to provide a historical time series of carbon emissions in the United States.

- Last year's emissions increase has been revised downward on both absolute and percentage bases. EIA's estimate of the emissions increase between 1995 and 1996 has fallen from 3.4 percent to 2.8 percent. Of the decrease in the estimate, 25 percent is due to a revision downward in the increment in carbon dioxide emissions, based primarily on changes in coal consumption data for the electric utility sector. The other 75 percent of the revision is based on the new methods outlined above for methane and nitrous oxide estimates. These changes to estimation methods were made to reflect better information in the case of methane and changes in IPCC guidelines in the case of nitrous oxide. The following chapters and related appendixes of this report provide a full discussion of the changes in estimation methods.

illustrates the relationship between anthropogenic (human-made) and natural emissions and absorption of the principal greenhouse gases.

Water Vapor. Water vapor, as noted above, is the most common greenhouse gas present in the atmosphere. It is emitted into the atmosphere in enormous volumes through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and snow. Water vapor is so plentiful in the atmosphere that additional emissions are unlikely to absorb any significant amount of infrared radiation. It is also likely that the amount of water vapor held in the atmosphere is generally in equilibrium, and that increasing emissions of water vapor would not increase atmospheric concentrations.[3] According to currently available information, anthropogenic water vapor emissions at the Earth's surface are unlikely to be an important element in either causing or ameliorating climate change.

Carbon Dioxide. Carbon is a common element on the planet, and immense quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved

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[3] Note, however, that changing air temperature from other causes will change the equilibrium amount of water vapor contained in the atmosphere. This may be a "feedback" effect acting to accelerate or slow global climate change.

in ocean water. All life on Earth participates in the "carbon cycle," by which carbon dioxide is extracted from the air by plants and decomposed into carbon and oxygen, with the carbon being incorporated into plant biomass and the oxygen released to the atmosphere. Plant biomass, in turn, ultimately decays (oxidizes), releasing carbon dioxide back into the atmosphere or storing organic carbon in soil or rock. There are vast exchanges of carbon dioxide between the ocean and the atmosphere, with the ocean absorbing carbon from the atmosphere and plant life in the ocean absorbing carbon from water, dying, and spreading organic carbon on the sea bottom, where it is eventually incorporated into carbonate rocks such as limestone.

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising.

The most important natural sources of carbon dioxide are releases from the oceans (90 billion metric tons per year), aerobic decay of vegetation (30 billion metric tons), and plant and animal respiration (30 billion metric tons).[4] Known anthropogenic sources (including deforestation) were estimated to account for about 7 billion metric tons of carbon per year in the early 1990s. The principal anthropogenic source is the combustion of fossil fuels, which accounts for about three-quarters of total anthropogenic emissions of carbon worldwide. Natural processes—primarily, uptake by the ocean and photosynthesis—absorb substantially all the naturally produced carbon dioxide and some of the anthropogenic carbon dioxide, leading to an annual net increase in carbon dioxide in the atmosphere of 3.1 to 3.5 billion metric tons.[5]

Methane. Methane is also a common compound. The methane cycle is less well understood than the carbon cycle. Natural methane is released primarily by anaerobic decay of vegetation, by the digestive tracts of termites in the tropics, and by several other lesser sources. The principal anthropogenic sources are leakages from the production of fossil fuels, human-promoted anaerobic decay in landfills, and the digestive processes of domestic animals. The main sources of absorption are thought to be decomposition (into carbon dioxide) in the atmosphere and decomposition by bacteria in soil. Known and unknown sources of methane are estimated to total about 600 million metric tons annually; known sinks (i.e., absorption by natural processes) total about 560 million metric tons. The annual increase in methane concentration in the atmosphere accounts for the difference of 35 to 40 million metric tons.

Nitrous Oxide. The sources and absorption of nitrous oxide are much more speculative than those for other greenhouse gases. The principal natural sources are thought to be bacterial breakdown of nitrogen compounds in soils, particularly forest soils, and fluxes from ocean upwellings. The primary human-made sources are enhancement of natural processes through application of nitrogen fertilizers, combustion of fuels, and certain industrial processes. The existence of significant unidentified sources of nitrous oxide has set off a search for new sources, one consequence of which has been recent revisions to the IPCC emissions estimations methods for nitrous oxide from nitrogen fertilization of soils. The most important sink is thought to be decomposition in the stratosphere. Worldwide, estimated known sources of nitrous oxide total 13 to 20 million metric tons annually, and known sinks total 10 to 17 million metric tons. The annual increase in concentrations in the atmosphere is thought to total about 4 million metric tons.

Halocarbons and Other Gases. In the twentieth century, human ingenuity has created an array of "engineered" chemicals, not normally found in nature, whose special characteristics render them particularly useful. Some engineered chemicals are also greenhouse gases. The best known of these chemicals are the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, "Freon-12." CFCs have many desirable features: they are relatively simple to manufacture, inert, nontoxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

Because of their long atmospheric lives, a portion of the CFCs emitted into the atmosphere eventually find their way into the stratosphere, where they can be destroyed by sunlight. This reaction, however, releases free chlorine atoms into the stratosphere, and the free chlorine atoms tend to combine with stratospheric

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[4] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 77.

[5] One metric ton equals 1.102 short tons.

ozone, which protects the surface of the Earth from certain wavelengths of potentially damaging solar ultraviolet radiation (ultraviolet radiation, for example, causes human and animal skin cancers). The destruction of stratospheric ozone, notwithstanding its potential damage to living organisms, exerts a net cooling effect on the surface of the planet, making the net effects of CFCs on radiative forcing ambiguous.

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a much longer time scale.

HFCs have no chlorine and consequently have no effect on the ozone layer, but they have potentially powerful direct effects on climate. HFCs were rare before 1990, but in 1994 HFC-134a was adopted as the standard motor vehicle air conditioning refrigerant in virtually all new cars made in America. Consequently, HFC emissions are now rising rapidly, though from a negligible base.

Beyond the halocarbons (CFCs, HFCs, and HCFCs) there are a range of engineered chemicals, produced in relatively small quantities, that also have direct radiative forcing effects. These include halocarbons such as perfluorocarbons (PFCs), which include CF_4, C_2F_6, and C_3F_8. PFCs are emitted as byproducts of aluminum smelting. Other chemicals such as sulfur hexafluoride (SF_6), used as an insulator in utility-scale electrical equipment, are not halocarbons but are potent greenhouse gases. Possibly, other chemicals not yet identified could exhibit similar radiative properties. All of these chemicals are potent greenhouse gases, because they combine relative scarcity in the atmosphere with very long atmospheric lifetimes.

Finally, the solvents carbon tetrachloride, methyl chloroform, and methylene chloride are regulated in the United States both as ozone depleters and for toxicity. All these gases have direct radiative forcing effects, which are offset to some degree by their ozone-depleting effects.

Criteria Pollutants That Affect Climate. There are three gases, emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), that have indirect effects on global warming: carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds (NMVOCs). These compounds, regulated in the United States pursuant to the Clean Air Act, are often referred to (along with particulates, lead, and sulfur dioxide) as “criteria pollutants.” The criteria pollutants are reactive compounds, and they tend to remain in the atmosphere for only hours or days. The sequence of reactions that removes them from the atmosphere, however, tends to promote the formation of ozone (O_3), a reactive and unstable molecular form of oxygen. Ozone in the stratosphere protects life on Earth from ultraviolet radiation, but ozone at ground level in high concentrations causes respiratory distress in people and animals and, also, is itself a potent (though short-lived) greenhouse gas.[6]

It has not proved possible to make a general determination of the contribution of criteria pollutants to global warming. The reactions that produce ozone are strongly affected by the relative concentrations of various pollutants, the ambient temperature, and local weather conditions. Emissions of criteria pollutants can create very high, though localized, ozone concentrations under favorable conditions (for example, a warm, sunny day combined with still air and low humidity) and negligible concentrations under unfavorable conditions. The criteria pollutants are included in this report for completeness.

Aerosols. Finally, there is a class of gases that probably exert a net cooling effect on the climate. These compounds create tiny solid particles (aerosols) in the atmosphere, which in turn act as nuclei for collections of water droplets and stimulate cloud formation. The clouds, in turn, reflect sunlight back into space, cooling the planet. The most important such gas is sulfur dioxide (SO_2), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds that are effective in promoting cloud formation. Sulfur dioxide emissions are regulated in the United States under the Clean Air Act, and their concentrations have declined considerably in recent years. Particulate emissions are also likely to exert a net cooling effect by promoting cloud formation.

[6] The U.S. Environmental Protection Agency has set a National Ambient Air Quality Standard for acceptable atmospheric concentrations of ozone at 0.12 parts per million. The standard was set on the basis that concentrations of this magnitude could cause respiratory distress in vulnerable individuals. Higher concentrations (above 0.3 parts per million) would cause respiratory distress for most individuals.

Units for Measuring Greenhouse Gases

In this publication, the EIA has elected to report information in forms that are most likely to be familiar to users of the document. Therefore, energy and industrial data are reported in their native units (usually international units). Oil production is reported in thousand barrels per day, and energy production and sales are reported in (higher heating value) British thermal units (Btu).

Emissions data are reported in metric units. We have attempted to bridge the gap between users of metric units and international units by using the familiar "million metric tons" common in European industry instead of the "gigagrams" favored by the scientific community.

Emissions of most greenhouse gases are reported here in terms of the full molecular weight of the gas (as in Table ES1). In Table ES2, however, and subsequently throughout the report, carbon dioxide is reported in carbon units, defined as the weight of the carbon content of carbon dioxide (i.e., just the "C" in CO_2). Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 44/12, or 3.67. This approach has been adopted for two reasons:

- Carbon dioxide is most commonly measured in carbon units in the scientific community. Scientists argue that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide. Because combustion is never perfect, some portion of the emissions consists of carbon monoxide, methane, other volatile organic compounds, and particulates. These other gases (particularly carbon monoxide) eventually decay into carbon dioxide, but it is not strictly accurate to talk about "tons of carbon dioxide" emitted.
- Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration. Because most fossil fuels are 75 to 90 percent carbon by weight, it is easy and convenient to compare the weight of carbon emissions (in carbon units) with the weight of the fuel burned. Similarly, carbon sequestration in forests and soils is always measured in tons of carbon, and the use of carbon units makes it simple to compare sequestration with emissions.

While carbon dioxide emissions can be measured in tons of carbon, emissions of other gases (such as methane) can also be measured in "carbon dioxide equivalent" units by multiplying their emissions (in metric tons) by their global warming potentials. For comparability, carbon dioxide equivalent units can be converted to "carbon equivalent" by multiplying by 12/44 (as in Table ES2) to provide a measure of the relative effects of various gases on climate.

Relative Forcing Effects of Various Gases

Some greenhouse gases are more potent in affecting global temperatures than are others. As a result, comparable increases in the concentrations of different greenhouse gases can have vastly different heat-trapping effects. Among those identified, carbon dioxide is among the least effective as a greenhouse gas. Other compounds, on a gram-per-gram basis, appear to have much greater effects.[7]

It would be useful to determine the precise relative effectiveness of various greenhouse gases in affecting the Earth's climate. That information would help policymakers know whether it would be more effective to concentrate effort on reducing the very small emissions of powerful greenhouse gases, such as HFC-134a, or whether they should direct their efforts to controlling the very large emissions of relatively ineffective gases, such as carbon dioxide.

There has been extensive study of the relative effectiveness of various greenhouse gases in trapping the Earth's heat. Such research has led to the development of the concept of a "global warming potential," or GWP. The GWP is intended to illustrate the relative impacts on global warming of various gases, compared with that of carbon dioxide. Over the past few years, the IPCC has conducted an extensive research program aimed at summarizing the effects of various greenhouse gases through a set of GWPs. The results of that work were released in 1995 in an IPCC report, *Climate Change 1994*[8] and updated in *Climate Change 1995*.[9]

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[7] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 22.

[8] Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

[9] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

The IPCC's work has established that the effects of various gases on global warming are too complex to permit them to be easily summarized as a single number. The complexity takes several forms:

- Each gas absorbs radiation in a particular set of wavelengths, or "window," in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the "window" will already have been captured, and the marginal effects of additional emissions will not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This "diminishing return" effect implies that increasing the concentration of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.
- Various natural processes cause many greenhouse gases to decompose into other gases or to be absorbed by the ocean or ground. These processes can be summarized in terms of the "atmospheric lifetime" of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere. Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant.
- Many gases are chemically active, and they may react in the atmosphere in ways that promote or hinder the formation of other greenhouse gases. For example, nitrogen oxides and carbon monoxide combine to promote the formation of ozone, which is a potent greenhouse gas, whereas CFCs tend to destroy atmospheric ozone, thus promoting global cooling. Such indirect effects have sometimes proved impossible to summarize in terms of global warming potentials. Indirect effects also imply that changes in relative concentrations of various greenhouse gases would tend to change their relative effects.

Despite such complexity, the scientific community is working to develop GWP approximations. Table 3 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales.

The IPCC has also devoted effort to the study of indirect and interaction effects of various gases—particularly the indirect effects of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) on the ozone layer—compared with their direct radiative forcing effects. The IPCC presented GWP estimates for the first time in 1996 that quantified the direct and indirect effects of certain CFCs and HCFCs. Certain chemicals (halon-1301 and carbon tetrachloride, for example) are now believed to exert a net cooling influence—i.e., to have a negative global warming potential. All the net GWPs for CFCs and HCFCs are considerably lower than their direct GWPs.[10]

Global Climate Change Policy Developments

Rising concentrations of carbon dioxide in the atmosphere were first detected in the late 1950s, and observations of atmospheric concentrations of methane, nitrous oxide, and other gases began in the late 1970s. Concern about the effects of rising atmospheric concentrations of greenhouse gases remained largely the province of atmospheric scientists and climatologists, however, until the mid-1980s, when a series of international scientific workshops and conferences began to move the topic onto the agenda of United Nations specialized agencies, particularly, the World Meteorological Office.

The IPCC was established under the auspices of the United Nations in late 1988, to accumulate available scientific research on climate change and to provide scientific advice to policymakers. A series of international conferences provided impetus for an international treaty aimed at limiting the human impact on climate. In December 1990, the United Nations established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (generally called the INC). Beginning in 1991, the INC

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[10] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 122.

Table 3. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide
(Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
Carbon Dioxide	Variable	1	1	1
Methane	12 ± 3	56	21	7
Nitrous Oxide	120	280	310	170
HFCs, PFCs, and Sulfur Hexafluoride				
HFC-23	264	9,200	12,100	9,900
HFC-125	33	4,800	3,200	11
HFC-134a	15	3,300	1,300	420
HFC-152a	2	460	140	42
HFC-227ea	37	4,300	2,900	950
Perfluoromethane	50,000	4,400	6,500	10,000
Perfluoroethane	10,000	6,200	9,200	14,000
Sulfur Hexafluoride	3,200	16,300	23,900	34,900

Note: The typical uncertainty for global warming potentials is estimated by the Intergovernmental Panel on Climate Change at ±35 percent.

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

hosted a series of negotiating sessions that culminated in the adoption, by more than 160 countries, including the United States, of the Framework Convention on Climate Change, opened for signature at the “Earth Summit” in Rio de Janeiro, Brazil on June 4, 1992.[11]

From the Framework Convention to the Kyoto Protocol

The objective of the Framework Convention is stated as follows:

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*[12]

To achieve this objective, the Framework Convention divided its signatories into two groups: the countries listed in Annex I to the Protocol, and all others. The Annex I countries are developed industrial states: the United States, Eastern and Western Europe, Russia and the Ukraine, Japan, Australia, New Zealand, and Canada.[13]

The Convention requires Annex I parties to the convention to undertake “policies and measures” to limit emissions of greenhouse gases, but there are no compulsory targets and no compulsory measures. It does require Annex I signatories to prepare national emissions inventories and to report to the Secretariat on the actions taken “with the aim of returning . . . to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases” (Article 4.2b).

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[11] The Framework Convention was “adopted” by a vote of the conference of the parties on May 9th, while the signatures and ratifications of member states flowed in over a period of years. The treaty “entered into force” in 1994. There is a discussion of the development of the Convention in D. Bodanzky, “Prologue to the Climate Convention,” in I. Mintzer and J.A. Leonard (eds.), *Negotiating Climate Change: The Inside Story of the Rio Convention* (Cambridge, UK: Cambridge University Press, 1994), pp. 49-66.

[12] The official text of the Framework Convention can be found at web site www.unfccc.de/index.html.

[13] The Annex I grouping has undergone a number of changes. Russia, the Ukraine, Latvia, Estonia, and Lithuania (but not the Central Asian Republics) are now part of Annex I. Belarus, which participated for a while, is no longer a party to the Kyoto Protocol. Turkey signed the Convention but subsequently withdrew from Annex I status. Czechoslovakia has divided into the Czech Republic and Slovakia, and two Yugoslav successor states, Croatia and Slovenia, have joined Annex I. Lichtenstein and Monaco have also joined the Kyoto Protocol.

In April 1993, President Clinton committed to stabilizing U.S. emissions of greenhouse gases at the 1990 level by 2000, using an array of voluntary measures. In the following years, however, greenhouse gas emissions in the United States and many other Annex I countries continued to increase. The climate negotiators, continuing to meet as "the Conference of the Parties [to the Framework Convention]," (COP), took up the question of how to limit emissions in the post-2000 period, a topic on which the Framework Convention was silent. In 1995, COP-1, held in Berlin, Germany, agreed to begin negotiating a post-2000 regime. In 1996, COP-2, held in Geneva, Switzerland, agreed that the regime would encompass quantitative limitations on emissions for the parties, to be signed at COP-3, which was to be held in Kyoto, Japan, in December 1997.

The Kyoto Protocol

The Kyoto Protocol to the Framework Convention, adopted on December 11th, is the most ambitious and far-reaching international environmental agreement ever attempted.[14] Its most fundamental feature is a set of quantified greenhouse gas emissions targets for Annex I countries, which collectively are about 5 percent lower than the 1990 emissions of these countries taken as a group. Developing countries signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a "quantified emissions reduction limitation commitment," which limits the signatory to some fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions. Both the European Union (EU) and the individual members of the EU signed the Protocol and are both individually and collectively responsible for meeting their commitments.
- **A Commitment Period.** Each target is defined as the average of the signatory's emissions over the 5-year period 2008-2012, called "the commitment period."
- **Six Gases.** Participants are to limit their emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride, weighted by the global warming potential of each gas. HFCs and PFCs are actually classes of gases with multiple members, but the term "six gases" has stuck. Participants may use 1995 as the baseline for HFCs, PFCs, and SF_6, instead of 1990.
- **Demonstrable Progress.** Annex I countries are required to have made "demonstrable progress" toward achieving their commitments by 2005.
- **Land Use and Forestry.** The Protocol includes complicated provisions on forestry, the implication being that some emissions and sequestration arising from changes in land use and forestry since 1990 can be counted against the target.
- **Flexibility Mechanisms.** The Protocol includes an array of flexibility mechanisms described at greater length below: "emissions trading," "joint implementation," "joint fulfillment," and the "Clean Development Mechanism."
- **Entry into Force.** The Protocol enters into force when 55 countries *and* Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions "have deposited their instruments of ratification, acceptance, approval, or accession." As of August 25, 1998, 50 countries (including 25 Annex I countries) had signed (not ratified) the Protocol. No country has ratified the Protocol to date.

The Kyoto Protocol and the United States

The U.S. Government, in the form of the Executive Branch, has "agreed to" (but not yet signed) the Kyoto Protocol and is actively negotiating the various subsidiary arrangements necessary to fully define the agreement.[15] The Senate, with a constitutional duty to "advise and consent" to the international undertakings of the United States, placed certain conditions (in advance) on the kind of instrument to which it would be prepared to consent. Those conditions were embodied in the Byrd-Hagel Resolution (S.Res. 98) a "sense of the Senate" resolution, which was passed by a vote of 95 to 0 on July 25, 1997. The Byrd-Hagel resolution specifies that:

> *(1) the United States should not be a signatory to any protocol to, or other agreement regarding, the United Nations Framework Convention on Climate Change of 1992, at negotiations in Kyoto in December 1997, or thereafter, which would—*
>
> *(A) mandate new commitments to limit or reduce greenhouse gas emissions for the Annex I Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions for*

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[14] The text of the Kyoto Protocol can also be found at web site www.unfccc.de/index.html.

[15] The Kyoto Protocol was adopted by a unanimous vote of the Conference of the Parties, including the favorable vote of a U.S. delegation endowed with plenipotentiary powers. The treaty was opened for signature on March 16, 1998. Under international law, signature is generally held to be sufficient to bind a country to an agreement. However, the domestic law of the United States and many other countries requires consent by the law-making power (usually the legislature) before a treaty can be binding. The Kyoto Protocol specifies that it will enter into force only upon ratification by a sufficient number of states.

> *Developing Country Parties within the same compliance period, or*
>
> *(B) would result in serious harm to the economy of the United States; and*
>
> *(2) any such protocol or other agreement which would require the advice and consent of the Senate to ratification should be accompanied by a detailed explanation of any legislation or regulatory actions that may be required to implement the protocol or other agreement and should also be accompanied by an analysis of the detailed financial costs and other impacts on the economy of the United States which would be incurred by the implementation of the protocol or other agreement.*

The Protocol has not yet been sent to the Senate.

U.S. emissions of greenhouse gases have increased at a compounded annual rate of 1.4 percent since 1990. In the context of a growing economy and low fossil fuel prices, similar increases are expected over the next 10 years. The EIA, in its "baseline" study of U.S. energy trends, projects that energy-related carbon dioxide emissions can be expected to increase at a 1.6-percent annual rate between 1996 and 2010, reaching a level of 1,803 million metric tons of carbon by 2010, some 550 million metric tons (34 percent) above the Kyoto target.[16] The same projection envisages a 2010 U.S. population some 23 percent larger than in 1996 (0.8-percent annual growth) and a gross domestic product some 47 percent greater (1.9-percent annual growth) than in 1996.

The nature and cost of possible policy interventions that would help the United States meet the Kyoto targets are uncertain and controversial. The President's Council of Economic Advisors estimates that the costs of compliance would be lower than suggested by other analyses of purely domestic costs, because of the domestic and international "flexibility" provisions of the Kyoto Protocol.[17] The key flexibility provisions are:

- The target, which instead of being just 2010, is the average of 2008-2012 emissions
- The ability to reduce emissions of gases other than carbon dioxide, including methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride
- The ability to include emissions reduced or avoided by "afforestation, reforestation, and deforestation" resulting from land use changes
- Joint implementation among Annex I countries
- Emissions trading among Annex I countries
- Use of the Clean Development Mechanism (CDM) to fund emissions-reducing actions in developing countries
- The "joint fulfillment" mechanism, adopted by the European Union.

Flexibility Provisions: Other Gases

In the Kyoto Protocol, not all reductions in greenhouse gas emissions must be in terms of energy-related carbon dioxide. Unlike carbon dioxide, the other greenhouse gases are often fugitive emissions, not necessarily central to the workings of modern industrial economies. Nitrous oxide and methane are naturally occurring substances, ubiquitous in nature, and rarely regulated. The engineered chemicals are usually inert, nontoxic, and also unregulated.

In some cases, emissions of other gases are correlated with energy-related carbon dioxide emissions, and limiting energy-related carbon dioxide emissions would also tend to limit emissions of the other gases. In an environment in which carbon dioxide emissions are significantly constrained, it may be possible to reduce emissions of the other gases. In the case of the United States, however, the other gases collectively account for only about 17 percent of total emissions. Thus, even large reductions in emissions of other gases would have a limited impact on total emissions, in the range of a few percent.

Flexibility Provisions: Land Use and Forestry

The forestry sections of the Kyoto Protocol are complex and difficult to understand. At the recent Bonn Meeting of the Subsidiary Body on Scientific and Technical Advice, the negotiators decided to commission the IPCC to prepare a special study with recommendations to the Conference of the Parties.[18] In general, the Kyoto Protocol provides that net "sinks" of carbon

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[16] Energy Information Administration, *Annual Energy Outlook 1998*, DOE/EIA-0383(98) (Washington, DC, December 1997), p. 124. See also web site www.eia.doe.gov/oiaf/aeo98/homepage.html. More recently, at the request of the Committee on Science of the U.S. House of Representatives, the EIA has prepared a Service Report on the domestic costs of implementing the Kyoto Protocol. See Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity*, SR/OIAF/98-03 (Washington, DC, October 1998), web site www.eia.doe.gov/oiaf/kyoto/kyotorpt.html.

[17] Council of Economic Advisors, *The Kyoto Protocol and the President's Policies To Address Climate Change: Administration Economic Analysis* (Washington, DC, July 1998). See web site www.whitehouse.gov.

[18] See *Report of the Subsidiary Body for Scientific and Technological Advice on Its Eighth Session, Bonn, 2-12 June 1998*, FCCC/SBSTA/1998/6 (August 10, 1998), web site www.unfccc.de/index.html.

arising from land use changes and forestry in the 2008-2012 period (including those in the United States) can count as changes in carbon stocks (net sequestration), so long as the changes are "measurable and verifiable" and are limited to changes caused by anthropogenic "afforestation, deforestation, and reforestation since 1990."[19]

As discussed in Chapter 6 of this report, much of the carbon sequestered through forestry and land use in the United States comes not from sequestering carbon in the form of trees (relatively easy to measure) but from sequestering carbon in roots and soil (much more uncertain). Table 4 offers a first approximation of the distinction, using the work of Birdsey and Heath.[20] According to this "business-as-usual" projection, the carbon stored in relatively easily measurable trees would account for 69 million metric tons of carbon, equivalent to about 5 percent of U.S. emissions. On the other hand, the harder-to-measure carbon stored in roots, soil, and forest floor is much larger: 123 million metric tons. Only a fraction of this pool would "count" toward the Kyoto target, however, because of the "afforestation, deforestation, and reforestation since 1990" clause of the treaty.

In principle, the Protocol requires partitioning forest land into two categories: "subject to afforestation, deforestation, and reforestation since 1990," and undisturbed since 1990. Carbon accumulated on land in the "since 1990" category would count, but carbon in the "undisturbed" category would not. The relative sizes of the two categories would be difficult to derive from current forest statistics. As a first approximation, however, about 4 million acres (0.6 percent) of U.S. forest are harvested annually, and another 4 million acres are lost to wildfire. Thus, whether wildfires "count" as "anthropogenic deforestation" turns out to be an important question. Assuming that wildfires do not count, at most about 12 percent of U.S. forest land will have been harvested and replanted between 1990 and 2010.

Carbon accumulation is not evenly distributed across U.S. forest lands, as Table 4 also illustrates. When projected sequestration is considered by ownership category, most of the harvested land will be in the "forest industry" category, although some portions of national forests are also harvested and replanted. Net sequestration in land owned by the forest industry is low precisely because the land is regularly harvested and reforested. Land in the "other public" and "other private" categories is probably rarely or never harvested and, consequently, might not "count" under the protocol, even if the land in these categories sequesters substantial amounts of carbon.

Flexibility Provisions: Emissions Trading Among Annex I Countries

The key flexibility provision of the Kyoto Protocol is the ability of Annex I countries to trade emissions among themselves, which would permit Annex I countries to meet their commitment amounts by buying and selling tons of greenhouse gas emissions. A crude calculation of the possible surpluses and deficits of the Annex I countries before any policy interventions occur can be made by using the projections of carbon dioxide

Table 4. Projected U.S. Forest Carbon Sequestration by Ownership Group and Source of Sequestration, 2010
(Million Metric Tons of Carbon)

Ownership	Trees and Understory	Roots, Soil, and Forest Floor	Total
National Forest	29	50	**79**
Other Public	14	36	**49**
Forest Industry	13	1	**14**
Other Private	5	30	**35**
Reserved and Other Forest Land	8	6	**14**
Total	**69**	**123**	**192**

Source: R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in *Productivity of America's Forests and Climate Change*, GM-GTR-271 (Fort Collins, CO: USDA Forest Service), pp. 64-65.

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[19] This discussion is closely linked to the U.S. situation and does not do full justice to the complexity of the issue or the difficulty of making the language of the Kyoto Protocol operational across other signatories. For a discussion of some of the issues of interpretation, see the note written by the Framework Convention Secretariat, "Methodological Issues: Issues Related to Land-Use Change and Forestry," FCCC/SBSTA/1998/INF.1 (May 18, 1998), web site www.unfccc.de/index.html.

[20] R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in *Productivity of America's Forests and Climate Change*, GM-GTR-271 (Fort Collins, CO: USDA Forest Service, 1995).

emissions in the EIA's *International Energy Outlook 1998*,[21] and comparing them with the Kyoto targets (Table 5).

Table 5 indicates that several countries of the former Soviet Union (Russia, Ukraine, and the Baltic Republics) might have targets in excess of their expected 2008-2012 emissions, even if they do nothing to limit future emissions. Such excess tons have been called "hot air." The size and ultimate disposition of these tons is one of biggest analytical complexities in determining the consequences of the Kyoto Protocol.

Flexibility Provisions: Joint Fulfillment

Under Article 4.1 of the Protocol, signatories may agree to fulfill their commitments jointly. This mechanism was designed for the European Union, but it is open to any group of Annex I countries that wish to use it. The group would have to commit itself in advance, at the time that the participants ratify the Protocol, and would have to develop a scheme for allocating the group target among the participants. In the case of the EU, the allocation was based on negotiation between EU member governments.

Flexibility Provisions: Transfers of Project Reductions

"Joint implementation" is a term of art, whose meaning has evolved with the passage of time. As originally intended, joint implementation was a mechanism by which discrete emissions reduction projects could be undertaken by private parties or governments outside their home countries. The U.S. Government hoped that joint implementation would evolve into a program in which emissions reductions "credits" would be exchanged for project financing. In the Kyoto Protocol, two parallel mechanisms implement the concept of joint implementation:

- Article 6 defines a mechanism under which projects undertaken within an Annex I country can generate emissions reduction units, which can then be transferred to another Annex I country. Article 6 transfers are not given a name in the Protocol, but

Table 5. Carbon Emissions in the Annex I Countries, 1990 and 2010, and Effects of the Kyoto Protocol in 2010

Country or Region	Million Metric Tons of Carbon				Percent Change	
	1990 Actual Emissions	2010 Baseline Projection	2010 Kyoto Target	Reduction From 2010 Baseline	From 1990 Actual	From 2010 Baseline
Annex I Industrialized Countries						
United States	1,346	1,803	1,252	552	-7	-31
Canada	126	170	118	52	-6	-30
Japan	274	342	258	85	-6	-25
Western Europe	971	1,101	893	208	-8	-19
Australia and New Zealand	90	119	97	22	8	-18
Total	**2,807**	**3,535**	**2,618**	**917**	**-7**	**-26**
Annex I Countries in Transition						
Former Soviet Union	991	792	991	-199	0	25
Eastern Europe	299	280	277	3	-7	-1
Total	**1,290**	**1,072**	**1,268**	**-196**	**-2**	**18**
Total Annex I Countries	**4,097**	**4,607**	**3,886**	**721**	**-5**	**-16**

Note: "Western Europe" includes several non-EU countries, including Norway and Switzerland, and some non-Annex I countries, such as Turkey. "Former Soviet Union" includes all of the countries of the former Soviet Union, including Belarus. Belarus and the Central Asian republics are not parties to the Kyoto Protocol, and thus have neither targets nor baselines. Russia and the Ukraine account for about 87 percent of "former Soviet Union" emissions. Several Eastern European countries are permitted baseline emissions for particular years prior to 1990. Consequently, Eastern Europe's actual Kyoto Target is somewhat higher than shown here.

Source: Energy Information Administration, *International Energy Outlook 1998*, DOE/EIA-0484(98) (Washington DC, April 1998), p. 16. See also web site www.eia.doe.gov/oiaf/ieo98/home.html.

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[21] Energy Information Administration, *International Energy Outlook 1998*, DOE/EIA-0484(98) (Washington, DC, April 1998), web site www.eia.doe.gov/oiaf/ieo98/home.html.

participants sometimes now refer to Article 6 transfers as "joint implementation."

- Article 12 defines a "clean development mechanism" under which projects undertaken outside of Annex I countries will generate "certified emissions reductions," which may then be transferred to Annex I countries to meet their emissions targets.

Article 6 project transfers among Annex I Countries are of interest primarily as an alternative mechanism for implementing Annex I emissions trading, with tons being transferred pursuant to individual projects and the transfers being recognized and debited or accrued by participating Governments.[22]

Flexibility Provisions: The Clean Development Mechanism

The CDM would create a flow of "emissions reductions units" from projects executed outside the Annex I countries, thus allowing these countries, as a group, to make smaller reductions in their total emissions than would otherwise be the case. Unlike joint implementation, CDM projects would be able to generate tons as early as 2000, with cumulative reductions accrued between 2000 and 2007 applied to the 2008-2012 commitment period. Article 12.3(b) specifies that Annex I countries may use CDM tons ". . . to contribute to compliance with part of their . . . commitments . . . ."

Several restrictions apply:

- The CDM is subject to an "additionality" provision, Article 12.5c: "Reductions in emissions that are additional to any that would occur in the absence of the certified project activity."
- CDM projects must be reviewed and certified by "operational entities to be designated by the Conference of the Parties" and are subject to "independent auditing and verification of project activities."

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[22] This discussion assumes that (unlike the CDM) "emissions reduction units" cannot be created under Article 6 but only transferred from one country to another pursuant to a particular project.

2. Carbon Dioxide Emissions

Overview

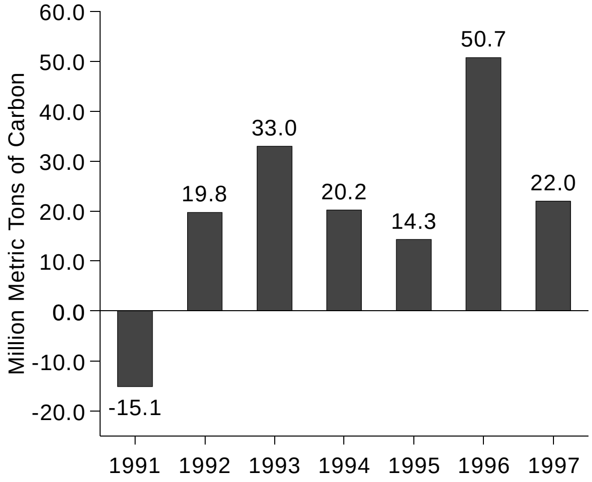
U.S. Anthropogenic Carbon Dioxide Emissions, 1990-1997

	Carbon Dioxide	Carbon Equivalent
Estimated 1997 Emissions (Million Metric Tons)	5,422.3	1,500.8
Change Compared to 1996 (Million Metric Tons)	80.7	22.0
Change from 1996 *(Percent)*	*1.5%*	*1.5%*
Change Compared to 1990 (Million Metric Tons)	531.3	144.9
Change from 1990 *(Percent)*	*10.7%*	*10.7%*

More than 98 percent of U.S. carbon dioxide emissions can be traced to the combustion of fossil fuels. Less than 2 percent comes from other industrial sources, including the manufacture of cement and lime. Total estimated emissions increased by 1.5 percent (22 million metric tons of carbon), from 1996 values of 1,479 million metric tons to 1,501 million metric tons of carbon in 1997 (Table 6).[23] Compared with 1990 emissions levels, the increase is 145 million metric tons of carbon or 10.7 percent. U.S. carbon emissions have increased every year since 1991 (Figure 1).

The substantial growth in U.S. carbon dioxide emissions between 1995 and 1996 can be traced principally to an increase in energy consumption due to weather-related factors. The more moderate increase from 1996 to 1997 is the product of different factors. First, robust 3.8-percent growth in the economy in 1997 led to an overall increase in end-use energy consumption of about 0.7 percent, including a 0.6-percent increase in demand for electricity. The increase in electricity use resulted in a 3.7-percent increment in emissions, because proportionally more fossil fuels were used for the generation of electricity than in 1996. Although hydroelectric generation was at historically high levels in 1997, as it had been in 1996, the increase was not enough to compensate for the temporary closing of several large nuclear power plants (about 2.6 gigawatts of generating capacity) and the permanent retirement of several smaller facilities (about 1.5 gigawatts). Compensation for the decrease in nuclear availability consisted largely of coal consumption, which was up by 2.9 percent in 1997 over 1996. Thus, carbon dioxide emissions from electricity generation rose much more rapidly than electricity consumption.

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-1997

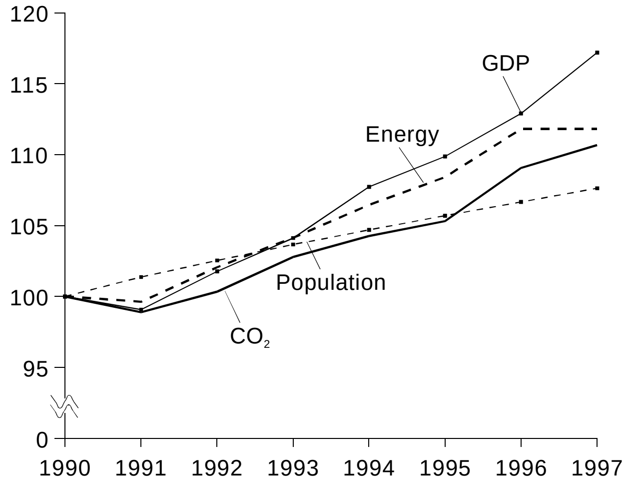


Source: Estimates presented in this chapter.

In times of slow or negative economic growth, U.S. carbon dioxide emissions have lagged behind population growth, as was seen in 1990, 1991, and 1992 (Figure 2). In recent years, however, with strong economic growth, carbon dioxide emissions have tended to grow more rapidly than population, although not as rapidly as the U.S. economy. The patterns of

[23] Carbon dioxide emissions are expressed in units of carbon in this report, except where they are otherwise identified. To obtain quantities of carbon dioxide from contained carbon multiply the amount times 3.667. See Appendixes A and B for a discussion of the estimation method.

Figure 2. Indices of U.S. Gross Domestic Product, Population, Energy Consumption, and Carbon Dioxide Emissions, 1990-1997



Sources: Carbon dioxide emissions are EIA estimates documented in this report. Energy consumption, gross domestic product (constant dollars), and population are reported in Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), pp. 5, 13, and 367.

growth in energy use and carbon dioxide emissions are similar but not identical. Residual differences are caused by changes in fuel mix.

The emergence of natural gas as a fuel for electricity generation has curbed the growth in U.S. carbon dioxide emissions since 1990. In the past 2 years, however, excess coal-fired generating capacity in the Midwest has provided an inexpensive source of electricity generation for those regions with transmission access. With the expansion of nuclear generation limited to increased operation of existing facilities, over the next several years the demand for fossil-fuel-generated electricity is likely to increase by more than overall demand for electricity.

Energy Consumption

Sectoral Analysis and Trends

The Energy Information Administration (EIA) partitions total energy consumption statistics into four end-use sectors: industrial, transportation, residential, and commercial. For all the sectors except transportation, a substantial portion of the energy used is consumed as electricity. The transportation sector uses mostly petroleum, smaller quantities of other fuels, and negligible amounts of electricity.

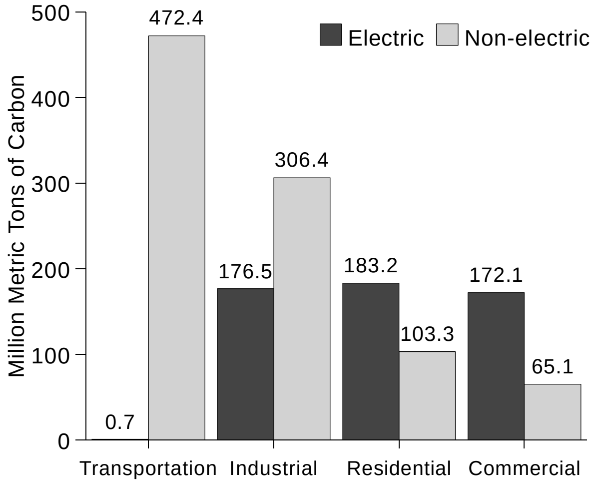
Energy End-Use Sector Sources of Carbon Dioxide Emissions, 1990-1997

	Million Metric Tons Carbon		*Percent Change*	
Sector	**1990**	**1997**	**1990-1997**	**1996-1997**
Transportation	432.1	473.1	*9.5%*	*0.5%*
Industrial	454.1	482.9	*6.3%*	*1.0%*
Commercial	206.8	237.2	*14.7%*	*4.9%*
Residential	253.1	286.5	*13.2%*	*0.3%*

Note: Electric utility emissions are distributed across sectors.

In this report, emissions for each sector are defined as the sum of emissions resulting from the direct burning of fuels plus emissions associated with the production of electric power (including losses) used in the sector. This approach makes sectoral analysis more meaningful; for example, about two-thirds of the carbon dioxide emissions in the residential and commercial sectors are derived from electricity (Figure 3). Electric power consumption has increased proportionately with growing end-use energy demands. The growth is significant,

Figure 3. Carbon Dioxide Emissions from Electric and Non-electric Sources by Energy End-Use Sector, 1997



Source: Estimates presented in this chapter.

because about 3 British thermal units (Btu) of energy are needed to deliver 1 Btu of end-use electricity.

Industrial Sector

Industrial primary energy consumption was about 32.9 quadrillion Btu in 1997, up by only 0.013 quadrillion Btu from 1996. In the United States, about one-third of all end-use carbon dioxide emissions are accounted for by the industrial sector (Table 7), which comprises manufacturing (the largest part of the sector), along with mining, construction, agriculture, fisheries, and forestry. Fossil fuel consumption is dominated by the need for heat and power; however, a substantial share of industrial petroleum use is for petrochemical feedstocks and other nonfuel uses that sequester carbon (Table 8). Natural gas and electricity consumption each account for about one-third of the energy consumed in the industrial sector.

Emissions of carbon dioxide from energy use in the industrial sector amounted to about 483 million metric tons of carbon in 1997, up by about 1 percent from the previous year (Table 9). Energy efficiency improvements, combined with low growth in energy-intensive industries, have moderated trends in carbon dioxide emissions at the same time that total industrial output has expanded. Between 1990 and 1997, emissions for this sector increased by 29 million metric tons of carbon, or about 6 percent—the lowest growth of any sector. In comparison, total industrial gross output grew by about 20 percent between 1990 and 1997.

Transportation Sector

Fuel use for transportation was about 24.8 quadrillion Btu in 1997. More than two-thirds of U.S. oil consumption is used for transportation, which accounts for about one-third of U.S. carbon dioxide emissions. Low fuel prices, low stock turnover of existing older vehicles, and stable average fuel efficiency in vehicles all contribute to expanding transportation energy consumption. In addition, of the vehicles purchased in recent years, a higher proportion of them have been sports utility vehicles or light trucks. Thus, even though fuel economy may be stable by category, the shift to less fuel-efficient vehicles has meant growing energy consumption and related emissions.

Motor gasoline accounts for nearly two-thirds of transportation sector energy consumption. Total carbon dioxide emissions in 1997 were 473 million metric tons (Table 10). Transportation sector emissions have yielded about 41 million metric tons of carbon, or 31 percent, of the national increase in emissions from energy end-use sectors since 1990 (Table 8).

This year, in keeping with international emissions accounting guidelines, carbon dioxide emissions from bunker fuels have been subtracted from the total for U.S. energy-related emissions for all years (see "Adjustments to U.S. Energy" in Table 6).

Residential and Commercial Sectors

In 1997, energy consumption in the residential and commercial sectors combined totaled 32.8 quadrillion Btu, up by 0.2 quadrillion Btu from 1996. The small increase represents the combination of different trends in the two sectors. Most of the emissions from the residential sector are associated with the use of natural gas and electricity for space heating and air conditioning and thus are subject to the vagaries of the weather. In 1996, emissions were up 5.7 percent over 1995 because of cold weather in regions that rely on natural gas. As a direct result, demand for natural gas increased, leading to a spike in natural gas prices, which further caused a shift from natural gas to coal where possible for electricity generation.

The return to more moderate weather in 1997 brought a leveling in emissions growth. Although residential energy demand fell by about 1 percent to about 18 quadrillion Btu in 1997, carbon dioxide emissions from the residential sector rose slightly—by 0.9 million metric tons of carbon (Table 11)—as a result of the increase in coal use and decrease in nuclear power for electricity generation. In the 7 years since 1990, residential emissions have accounted for 33 million metric tons of carbon, or about 25 percent, of the increase in carbon dioxide emissions from all energy end-use sectors (Table 7).

In contrast to the residential sector, energy consumption in the commercial sector was about 14.8 quadrillion Btu in 1997—up by about 3 percent over 1996. Again, because of the increase in coal use for electricity generation, the increase in carbon dioxide emissions was even larger, at 4.9 percent. With the overall economy growing by 3.8 percent in 1997 and the service component of the economy leading that growth, the commercial sector (which includes the service component) grew most rapidly. As a result, energy demand and related emissions from the commercial sector increased.

Electricity use accounts for more than one-half of commercial energy demand, with lighting the largest single use. The commercial sector contributes the smallest share of carbon dioxide emissions among the end-use sectors, making up about 16 percent of the total. Because this sector includes all business establishments that are not engaged in transportation, manufacturing, or other industrial activities (agriculture, mining, or construction), most of the energy consumed is electricity and natural gas. Commercial sector carbon dioxide emissions increased by 11 million metric tons, from 226 million metric tons in 1996 to 237 million metric tons of carbon in 1997 (Table 12). Between 1990 and 1997, the commercial sector accounted for 30 million tons of carbon, or about 23 percent of the total increase in U.S. carbon dioxide emissions from the energy end-use sectors. Commercial emissions have risen the most on a percentage basis and are up a total of 15 percent over 1990.

Electric Utilities

Electric Utility Carbon Dioxide Emissions by Fuel Input, 1990 and 1997

	Million Metric Tons Carbon		*Percent Change*	
Fuel	**1990**	**1997**	**1990-1997**	**1996-1997**
Petroleum	26.6	17.6	*-33.8%*	*14.4%*
Natural Gas	41.2	43.8	*6.2%*	*8.7%*
Coal	409.0	471.0	*15.1%*	*2.9%*
Geothermal	0.1	*	*-36.3%*	*4.5%*
Total	**476.9**	**532.4**	***11.6%***	***3.7%***

*Less than 0.05 million metric tons.

Although end users create the demand for electricity, electricity producers (primarily electric utilities) make decisions about how to meet that demand, based on fuel prices and capacity availability. In 1997, sales of electric power increased by only 0.6 percent, but utility carbon dioxide emissions increased by about 3.7 percent (Table 13), because coal-fired generation met a larger share of the demand for electricity.

Despite utility efforts to improve generation efficiency and demand-side management programs that have kept emissions lower than they otherwise would have been, carbon dioxide emissions from the burning of fossil fuels to meet end-use demand accounted for an increase of 55 million metric tons of carbon between 1990 and 1997. Coal, which in recent years has fueled about one-half of all U.S. electric power generation, produces more carbon dioxide emissions per kilowatthour of electricity generated than do other fossil fuels. The existence of underused coal-fired capacity in the United States may be contributing to the current increase in coal use.

Industrial Sources

U.S. Carbon Dioxide Emissions from Industrial Sources, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Carbon)	30.3
Change Compared to 1996 (Million Metric Tons Carbon)	0.2
Change from 1996 *(Percent)*	*0.8*
Change Compared to 1990 (Million Metric Tons Carbon)	5.5
Change from 1990 *(Percent)*	*22.0%*

Recent Trends

Industrial emissions not caused by the combustion of fossil fuels accounted for only about 1.9 percent of total U.S. carbon dioxide emissions in 1997. Emissions from these sources depend largely on the level of activity in the construction industries and on production at oil and gas wells. These sources include limestone and dolomite calcination, soda ash manufacture and consumption, carbon dioxide manufacture, and aluminum production.

Energy Production

When fossil fuels are burned, carbon dioxide is emitted to the atmosphere as a combustion product. In addition, oil and gas production leads to emissions of carbon dioxide from sources other than the combustion of commercial fuels, including the following:

- Natural gas flared, either because the cost of bringing the gas to market is prohibitive or because the gas is of insufficient quality to sell
- Carbon dioxide scrubbed from natural gas (to improve its heat content and quality) and subsequently vented to the atmosphere
- Carbon dioxide originally injected into the ground to increase oil recovery and subsequently vented into the atmosphere after being recovered in conjunction with the oil
- Flaring of “off spec” gases and fuels in gas plant, refinery, and chemical plant flares.

The EIA has always estimated emissions from flaring of natural gas. This year, carbon dioxide emissions have been revised upward (and methane emissions have been revised downward) as a result of the assumption that essentially all the gas reported as "vented and flared" is actually flared. Emissions from this source are less than 5 million metric tons of carbon annually.

The EIA has also, for the first time this year, estimated the quantities of carbon dioxide scrubbed from natural gas and released to the atmosphere, by computing the difference between the estimated carbon dioxide content of raw gas and the carbon dioxide content of pipeline gas. Estimated emissions from this source are about 4 million metric tons of carbon annually.

Emissions of carbon dioxide from enhanced oil recovery are excluded from this report because of a lack of information. The EIA believes that most of the carbon dioxide recovered with the oil is recycled, so that annual emissions are a fraction of the carbon dioxide recovered, which in turn is probably less than the volume of carbon dioxide injected. Emissions from this source may be included in future reports.

Combustion of "off spec" gases and fuels is not covered as a separate line item in this report, but much of the emissions from this source may be included in the "flaring" category described above or as industrial consumption of "still gas" by refineries.

Emissions from these energy production sources are conceptually separate, but they may overlap as a result of imprecision in the reporting of U.S. natural gas production and processing. Thus, emissions from these sources may include both undercounting and double counting to some degree, and the estimates should be considered more uncertain than those for emissions from reported energy consumption.

Industrial Processes

Carbon dioxide emissions from industrial processes account for about 17 to 19 million metric tons of carbon per year (Table 14). Since 1990, these emissions have increased, but higher emissions from cement manufacture and limestone consumption have been partially offset by lower emissions from aluminum manufacture. More than one-half of the emissions from industrial processes are from cement manufacture. When calcium carbonate is heated (calcined) in a kiln, it is converted to lime and carbon dioxide. The lime is combined with other materials to produce clinker (an intermediate product from which cement is made), and the carbon dioxide is released to the atmosphere. In 1997, the United States manufactured an estimated 81 million metric tons of cement, resulting in the release of carbon dioxide containing about 10 million metric tons of carbon into the atmosphere.

There are numerous other industrial processes in which carbonate minerals are used in ways that release carbon dioxide into the atmosphere, including the use of limestone in flue gas desulfurization and the manufacture and some uses of soda ash. Approximately 5 million metric tons of carbon per year are contained in emissions from these sources. Carbon dioxide is also released during aluminum smelting, when carbon anodes (with the carbon derived from nonfuel use of fossil fuels) are vaporized in the presence of aluminum oxide.

Adjustments to Energy Consumption

Under the Framework Convention on Climate Change, parties to the agreement committed to providing information on emissions trends, using methods that would facilitate international comparison of emissions estimates. To support such comparisons, a generalized reporting format was adopted. The format differs slightly from that used in the preparation of U.S. national energy statistics, primarily with respect to the method of calculating U.S. energy consumption, as well as its scope with regard to U.S. territories and bunker fuels for international transport.

EIA's energy data for the United States cover the 50 States and the District of Columbia but not the U.S. territories. Bunker fuels (fuel consumed by ships and aircraft fueled in the United States and engaged in international trade) are subsumed in EIA's transportation sector energy consumption data. In contrast, energy data used by the International Energy Agency for the United States include U.S. territories and exclude bunker fuels. Collectively, these differences in treatment can produce variations of several percentage points in reported energy consumption and, hence, in estimates of carbon dioxide emissions. Therefore, the EIA subtracts the bunker fuel emissions and adds the emissions of U.S. territories as "adjustments to energy" in order to make this estimate of emissions conform more closely to international emissions accounting guidelines.

U.S. Territories

In this report, carbon dioxide emissions for the U.S. territories (Puerto Rico, Virgin Islands, Guam, American Samoa, Micronesia, and Wake Island) are included as an adjustment. Their combined energy consumption is only about 0.5 quadrillion Btu and is concentrated on petroleum products; only Puerto Rico uses coal. Together, they are estimated to have emitted almost 12.3 million metric tons of carbon in 1997 (Table 6).

Bunker Fuels

In this report, emissions from bunker fuels are subtracted from the estimates of carbon dioxide emissions from energy consumption in keeping with the IPCC method. The estimate is based on purchases of fuel by ocean-going ships in U.S. ports and by international air carriers in U.S. airports. In 1997, bunker fuel emissions of carbon dioxide produced about 19 million metric tons of carbon (Table 6).

Table 6. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-1997
(Million Metric Tons of Carbon)

Fuel Type or Process	1990	1991	1992	1993	1994	1995	1996	P1997
Energy Consumption								
Petroleum	591.4	576.9	587.6	588.8	601.3	597.4	620.6	627.5
Coal	481.5	475.7	478.1	494.4	495.6	500.2	520.9	533.0
Natural Gas	273.2	278.1	286.3	296.6	301.5	314.1	319.1	319.1
Geothermal	0.1	0.1	0.1	0.1	*	*	*	*
Total Energy Consumption	**1,346.1**	**1,330.8**	**1,352.1**	**1,379.8**	**1,398.4**	**1,411.7**	**1,460.6**	**1,479.6**
Adjustments to U.S. Energy								
U.S. Territories	8.7	9.9	9.5	10.7	10.8	11.6	11.9	12.3
Bunker Fuels	-21.9	-23.1	-24.4	-22.0	-21.5	-22.8	-21.7	-19.4
Total Adjustments	**-3.2**	**-13.2**	**-14.9**	**-11.3**	**-10.7**	**-11.2**	**-9.8**	**-7.1**
Other Sources								
CO_2 in Natural Gas	3.6	3.7	3.9	4.1	4.3	4.2	4.5	4.6
Cement Production	8.9	8.7	8.8	9.3	9.8	9.9	9.9	10.1
Other Industrial	8.0	8.0	8.0	8.0	8.1	8.9	9.1	9.2
Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.3
Total Other Sources	**23.0**	**23.2**	**23.5**	**25.1**	**26.1**	**27.6**	**28.0**	**28.2**
Total	**1,355.9**	**1,340.8**	**1,360.6**	**1,393.6**	**1,413.8**	**1,428.1**	**1,478.8**	**1,500.8**

*Less than 0.05 million metric tons.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Emissions coefficients are annualized for coal, motor gasoline, liquefied petroleum gases, jet fuel, and crude oil. Includes emissions from bunker fuels. Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 7. U.S. Carbon Dioxide Emissions from Fossil Energy Consumption by End-Use Sector, 1990-1997
(Million Metric Tons of Carbon)

End Use	1990	1991	1992	1993	1994	1995	1996	P1997
Energy Consumption								
Residential	253.1	257.2	256.0	271.8	268.4	270.3	285.6	286.5
Commercial	206.8	206.4	205.5	212.1	213.9	217.9	226.0	237.2
Industrial	454.1	442.7	459.2	458.8	467.4	465.0	478.3	482.9
Transportation	432.1	424.5	431.4	436.7	449.5	458.5	470.7	473.1
Total Energy	**1,346.1**	**1,330.8**	**1,352.1**	**1,379.3**	**1,399.1**	**1,411.7**	**1,460.6**	**1,479.6**
Electric Utility[a]	476.9	473.5	473.0	490.7	494.1	495.3	513.3	532.4

[a] Estimates of additional carbon dioxide emissions from the use of flue gas desulfurization are included in Table 14.

P = preliminary data.

Notes: Includes energy from petroleum, coal, and natural gas. Electric utility emissions are distributed across consumption sectors. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 8. U.S. Carbon Sequestered by Nonfuel Use of Energy, 1990-1997
(Million Metric Tons of Carbon)

End Use	1990	1991	1992	1993	1994	1995	1996	P1997
Industrial								
Petroleum								
Liquefied Petroleum Gases	16.2	18.6	18.7	18.2	20.9	21.4	22.2	22.3
Distillate Fuel	0.4	0.6	0.5	0.5	0.5	0.5	0.5	0.5
Residual Fuel	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Asphalt and Road Oil	24.1	22.2	22.7	23.7	24.2	24.3	24.2	25.2
Lubricants	1.9	1.7	1.7	1.8	1.8	1.8	1.7	1.8
Other	19.4	19.0	20.1	22.1	22.9	23.5	24.1	25.6
Pentanes Plus	1.2	0.7	0.9	4.0	3.8	4.4	4.7	4.3
Petrochemical Feed	12.6	12.6	13.4	13.6	14.1	13.6	13.8	15.9
Petroleum Coke	2.2	1.9	3.0	1.8	2.1	2.7	2.9	2.5
Waxes and Miscellaneous	3.4	3.7	2.7	2.7	2.9	2.7	2.7	2.8
Coal	0.4	0.4	0.8	0.6	0.5	0.6	0.5	0.5
Natural Gas	4.1	3.9	3.5	4.0	5.0	5.1	5.4	5.7
Transportation								
Lubricants	1.8	1.6	1.6	1.7	1.7	1.7	1.6	1.7
Total	**68.3**	**67.9**	**69.7**	**72.5**	**77.6**	**78.9**	**80.5**	**83.4**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Source: EIA estimates documented in this chapter and in Appendix A.

Table 9. U.S. Carbon Dioxide Emissions from Energy Use in the Industrial Sector, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum								
Motor Gasoline	3.5	3.7	3.7	3.5	3.7	3.9	3.9	4.0
LPG	12.0	12.1	12.7	12.1	12.9	12.7	13.9	14.3
Distillate Fuel	22.9	21.9	22.1	21.2	21.4	20.8	21.6	22.1
Residual Fuel	8.8	7.1	8.2	9.5	9.0	7.2	6.5	5.7
Lubricants	1.9	1.7	1.7	1.7	1.8	1.8	1.7	1.8
Kerosene	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4
Other	51.8	48.7	55.7	50.0	52.5	49.4	55.7	57.5
Total	**101.1**	**95.4**	**104.3**	**98.3**	**101.7**	**96.0**	**103.7**	**105.8**
Coal	68.4	64.8	62.5	62.1	62.6	62.3	59.8	58.5
Natural Gas	118.3	120.2	125.9	130.8	133.4	140.2	144.0	142.2
Electricity	166.2	162.3	166.5	167.6	169.7	166.5	170.7	176.5
Total	**454.1**	**442.7**	**459.2**	**458.8**	**467.4**	**465.0**	**478.3**	**482.9**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0535(98/07) (Washington, DC, July 1998); and emissions coefficients shown in Table B1 of this report.

Table 10. U.S. Carbon Dioxide Emissions from Energy Use in the Transportation Sector, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum								
Motor Gasoline	260.9	259.5	263.4	269.3	273.7	279.9	285.2	288.3
LPG	0.4	0.3	0.3	0.3	0.6	0.3	0.3	0.3
Jet Fuel	60.1	58.1	57.6	58.1	60.4	60.0	62.7	63.3
Distillate Fuel	75.7	72.6	75.3	77.3	82.5	85.1	89.8	91.6
Residual Fuel	21.9	22.0	23.0	19.4	19.1	19.7	19.2	15.9
Lubricants	1.8	1.6	1.6	1.6	1.7	1.7	1.6	1.7
Aviation Gas	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
Total	**421.6**	**414.9**	**421.9**	**426.8**	**438.6**	**447.4**	**459.5**	**461.9**
Natural Gas	9.8	8.9	8.8	9.3	10.2	10.4	10.6	10.5
Electricity	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7
Total	**432.1**	**424.5**	**431.4**	**436.7**	**449.5**	**458.5**	**470.7**	**473.1**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0535(98/07) (Washington, DC, July 1998); and emissions coefficients shown in Table B1 of this report.

Table 11. U.S. Carbon Dioxide Emissions from Energy Use in the Residential Sector, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum								
LPG	6.3	6.7	6.6	6.8	6.8	6.9	7.3	7.4
Distillate Fuel	16.5	16.4	17.1	18.0	17.4	17.4	18.3	18.6
Kerosene	1.2	1.4	1.3	1.5	1.3	1.5	1.7	1.8
Total	**24.0**	**24.5**	**24.9**	**26.3**	**25.4**	**25.8**	**27.3**	**27.8**
Coal	1.6	1.4	1.5	1.5	1.4	1.4	1.4	1.4
Natural Gas	65.1	67.5	69.4	73.4	71.7	71.8	77.5	74.1
Electricity	162.5	163.8	160.2	170.6	169.8	171.4	179.4	183.2
Total	**253.1**	**257.2**	**256.0**	**271.8**	**268.4**	**270.3**	**285.6**	**286.5**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0535(98/07) (Washington, DC, July 1998); and emissions coefficients shown in Table B1 of this report.

Table 12. U.S. Carbon Dioxide Emissions from Energy Use in the Commercial Sector, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum								
Motor Gasoline	2.1	1.6	1.5	0.6	0.5	0.4	0.4	0.4
LPG	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3
Distillate Fuel	9.6	9.5	9.2	9.2	9.2	9.1	9.5	9.7
Residual Fuel	5.0	4.5	4.1	3.7	3.7	3.1	2.9	2.5
Kerosene	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.5
Total	**18.0**	**17.1**	**16.1**	**14.9**	**14.9**	**14.1**	**14.6**	**14.4**
Coal	2.4	2.2	2.2	2.2	2.1	2.1	2.1	2.1
Natural Gas	38.8	40.4	41.5	43.1	42.9	44.9	46.7	48.6
Electricity	147.5	146.7	145.6	151.9	153.9	156.8	162.5	172.1
Total	**206.8**	**206.4**	**205.5**	**212.1**	**213.9**	**217.9**	**226.0**	**237.2**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0535(98/07) (Washington, DC, July 1998); and emissions coefficients shown in Table B1 of this report.

Table 13. U.S. Carbon Dioxide Emissions from Electric Utilities, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum	**26.6**	**25.1**	**20.3**	**22.5**	**20.6**	**14.0**	**15.4**	**17.6**
Heavy Fuel Oil	24.2	22.9	18.2	20.0	18.0	11.6	12.9	14.7
Light Fuel Oil	1.7	1.6	1.3	1.5	1.9	1.8	1.9	1.7
Petroleum Coke	0.7	0.6	0.8	1.0	0.7	0.6	0.6	1.2
Coal	**409.0**	**407.3**	**411.9**	**428.6**	**429.4**	**434.4**	**457.5**	**471.0**
Natural Gas	**41.2**	**41.1**	**40.7**	**39.5**	**44.0**	**46.8**	**40.3**	**43.8**
Geothermal	**0.1**	**0.1**	**0.1**	*****	*****	*****	*****	*****
Total	**476.9**	**473.5**	**473.0**	**490.7**	**494.1**	**495.3**	**513.3**	**532.4**

*Less than 0.05 million metric tons.

P = preliminary data.

Notes: Independent Power Producers and cogeneration facilities are included in industrial emissions. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0535(98/07) (Washington, DC, July 1998); and emissions coefficients shown in Table B1 of this report.

Table 14. U.S. Carbon Dioxide Emissions from Industrial Sources, 1990-1997
(Million Metric Tons of Carbon)

Source	1990	1991	1992	1993	1994	1995	1996	P1997
Cement Manufacture								
Clinker Production	8.90	8.66	8.75	9.25	9.82	9.85	9.91	10.12
Masonry Cement	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	**8.91**	**8.68**	**8.77**	**9.27**	**9.84**	**9.87**	**9.93**	**10.14**
Other Industrial								
Limestone Consumption								
Lime Manufacture	3.39	3.36	3.47	3.63	3.70	3.96	4.09	4.13
Iron Smelting	0.47	0.44	0.37	0.31	0.30	0.31	0.30	0.33
Steelmaking	0.08	0.09	0.07	0.13	0.15	0.14	0.11	0.09
Copper Smelting	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Glass Manufacture	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.08
Flue Gas Desulfurization	0.52	0.55	0.54	0.51	0.61	0.77	0.81	0.81
Total	**4.54**	**4.50**	**4.54**	**4.67**	**4.87**	**5.30**	**5.45**	**5.50**
Dolomite Consumption	0.09	0.10	0.08	0.07	0.08	0.06	0.06	0.06
Soda Ash Manufacture	0.92	0.92	0.94	0.91	0.92	1.04	1.03	1.08
Soda Ash Consumption								
Glass Manufacture	*	*	*	*	*	*	*	*
Flue Gas Desulfurization	0.49	0.52	0.51	0.48	0.58	0.72	0.76	0.76
Sodium Silicate	0.05	0.05	0.05	0.06	0.06	0.07	0.06	0.06
Sodium Tripolyphosphate	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	**0.58**	**0.61**	**0.59**	**0.58**	**0.67**	**0.83**	**0.86**	**0.86**
Carbon Dioxide Manufacture	0.24	0.25	0.26	0.26	0.27	0.29	0.30	0.31
Aluminum Production	1.62	1.65	1.62	1.48	1.32	1.35	1.43	1.44
Shale Oil Production	0.05	*	0.00	0.00	0.00	0.00	0.00	0.00
Total Other Industrial	**8.04**	**8.03**	**8.03**	**7.97**	**8.13**	**8.85**	**9.12**	**9.24**
Total	**16.96**	**16.71**	**16.80**	**17.25**	**17.98**	**18.73**	**19.06**	**19.38**

*Less than 0.005 million metric tons.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Methodologies and sources of trend data documented in Appendix A.

3. Methane Emissions

Overview

U.S. Anthropogenic Methane Emissions, 1990-1997

	Methane	Carbon Equivalent
Estimated 1997 Emissions (Million Metric Tons)	29.1	166.7
Change Compared to 1996 (Million Metric Tons)	*	-0.2
Change from 1996 *(Percent)*	*-0.1%*	*-0.1%*
Change Compared to 1990 (Million Metric Tons)	-1.1	-6.2
Change from 1990 *(Percent)*	*-3.6%*	*-3.6%*

*Less than 0.05 million metric tons.

Estimated U.S. anthropogenic methane emissions totaled 29.1 million metric tons in 1997, down slightly from the 29.2 million metric tons estimated for 1996 and about 1.1 million metric tons below 1990 levels (Table 15). The 29.1 million metric tons of methane emitted in 1997 were equivalent to 167 million metric tons of carbon—about 9.2 percent of total U.S. greenhouse gas emissions—after accounting for the heat trapping capacity of the gas. Estimates of methane emissions are more uncertain than carbon dioxide emissions estimates. U.S. energy consumption is carefully tracked, and because most carbon dioxide emissions are the result of fossil fuel combustion, estimates of carbon dioxide emissions are likely to be accurate to within 3 to 5 percent. In contrast, methane emissions usually are accidental or incidental to biological processes and may not be metered in any systematic way.[24] Thus, methane emissions are difficult to calculate and often rely on proxy measurements. As a result, estimates of methane emissions are significantly more uncertain than estimates of carbon dioxide emissions.

Because of limitations on data availability and the inability to develop plausible proxies, emissions from two known sources—associated gas at oil wells and industrial wastewater—are not estimated in this report. These sources may be significant, and their exclusion clearly biases overall U.S. estimates downward (see boxes on pages 30 and 33). Total estimated U.S. anthropogenic emissions for 1997 also include preliminary data for several key sources; thus, the overall estimate must be described as preliminary. Emissions from two of these sources, coal mining and oil and gas systems, are substantial, together accounting for almost one-third of all U.S. methane emissions. Coal production data on a mine-by-mine basis will not be available until December 1998. Estimates for emissions from coal mines are scaled to national-level production data for 1997 that are already available. Similarly, estimates of emissions from oil and gas systems in 1997 are scaled to total gas throughput for the year, because detailed industry activity data are not yet available.

Major Sources of U.S. Methane Emissions, 1990-1997

	Million Metric Tons Methane		*Percent Change*	
Source	1990	1997	1990-1997	1996-1997
Energy	10.8	10.0	*-7.4%*	*1.1%*
Waste Management	11.1	10.4	*-6.6%*	*-1.5%*
Agriculture	8.2	8.6	*5.2%*	*0.2%*
Industrial Processes	0.1	0.1	*13.1%*	*0.1%*

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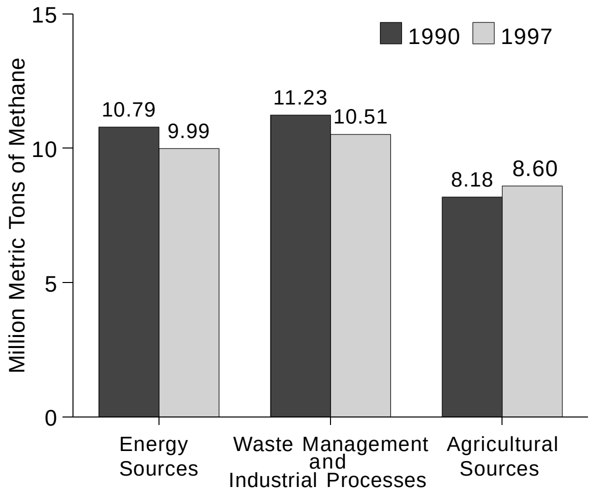
[24] Wherever possible, estimates of methane emissions are based on measured data. In some cases, however, measured data are incomplete or unavailable. In the absence of measured data, emissions are calculated by multiplying some known activity data, such as coal production or natural gas throughput, by an emissions factor derived from a small sample of the relevant emissions source or through laboratory experiments. For more detailed discussion of where measured data were used and how emissions factors were developed, see Appendix A. The absence of measured emissions data for most sources of methane emissions and the reliance on emissions factors represent a significant source of uncertainty (see Appendix C).

There are four principal sources of U.S. methane emissions: energy production and consumption, waste management, agriculture, and industry. Emissions from energy sources, which represent just over one-third of all U.S. methane emissions (Figure 4), declined significantly between 1990 and 1997 as a result of a substantial drop in emissions from coal mining. Methane emissions from waste management account for another one-third of the total. Emissions from this source also decreased between 1990 and 1997 as the share of municipal solid waste generated that was recycled increased, and greater amounts of methane generated from the decomposition of waste in landfills was captured and used for energy production. Emissions from agriculture represent about 30 percent of all U.S. methane emissions. Driven by livestock populations, emissions from agriculture peaked in 1995 and have since begun to decline.

Figure 4. U.S. Methane Emissions by Source, 1990 and 1997



Source: Estimates presented in this chapter.

Energy Sources

U.S. methane emissions from energy sources were estimated at 10.0 million metric tons in 1997, up 100,000 metric tons from 1996 levels but 800,000 metric tons below the 10.8 million metric tons emitted in 1990. The 7.4-percent decrease between 1990 and 1997 resulted almost entirely from lower emissions from coal mines. Emissions from coal mines dropped by 26 percent or about 1.1 million metric tons between 1990 and 1997. The amount of methane recovered from coal mines and used as an energy resource more than tripled, and industry consolidation lowered emissions from the Nation's gassiest mines. A decrease of 120,000 metric tons in estimated emissions from stationary combustion made a smaller contribution to the overall drop in emissions from energy sources. Together, the declines in emissions from coal mining and stationary combustion overwhelmed the increase of 500,000 metric tons in emissions from the oil and gas system attributed to increasing U.S. consumption of natural gas between 1990 and 1997.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	3.1
Change Compared to 1996 (Million Metric Tons Methane)	0.2
Change from 1996 *(Percent)*	*6.7%*
Change Compared to 1990 (Million Metric Tons Methane)	-1.1
Change from 1990 *(Percent)*	*-26.3%*

The preliminary estimate of methane emissions from coal mines for 1997 is 3.1 million metric tons, an increase of 6.7 percent from the 1996 level. The increase is due primarily to a 7.6-percent increase in ventilation emissions from gassy mines. Between 1990 and 1997, methane emissions from coal mines dropped by more than 25 percent from the 1996 level of 4.26 million metric tons. The decline is attributed to three important trends: (1) methane recovery from active coal mines for use as an energy resource increased from 250,000 metric tons in 1990 to more than 900,000 metric tons in 1997; (2) methane drainage from active mines decreased by almost 200,000 metric tons between 1990 and 1997; and (3) methane emissions from ventilation systems at gassy mines dropped by more than 250,000 metric tons (Table 16).

The estimates of methane emissions from coal mining for 1990-1997 have been revised substantially downward from estimates that appeared in the October 1997 edition of *Emissions of Greenhouse Gases in the United States.* The revisions are based on new information published by the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, on methane recovery operations and drainage from degasification systems.[25] Emissions from degasification are estimated to be on the order of 300,000 metric tons lower than previously believed. Meanwhile, methane recovery has grown more rapidly than previously reported, largely due to significant growth in Virginia.

The increase in methane recovery can be traced directly to new regulations promulgated by the Virginia Department of Oil and Gas in 1990 to encourage coalbed methane development. Beginning in 1992, CONSOL Coal Group began recovering gas at the Buchanan No. 1 mine. In 1993, CONSOL acquired Island Creek Coal and the very gassy VP No. 3, VP No. 5, and VP No. 6 mines, and later combined VP No. 5 and VP No. 6 into VP No. 8. CONSOL has since recovered gas from VP No. 3 and VP No. 8, in addition to Buchanan No. 1. In December 1995, CONSOL sold the gas rights from these mines to MCNIC Oil and Gas.[26] The methane recovered from these three mines is responsible for more than 0.5 million metric tons of the increase in methane recovery. Similar language aimed at bolstering coalbed methane development was included in the Energy Policy Act of 1992 and in legislation enacted in West Virginia during 1994.

The decrease in ventilation emissions from gassy mines is a function of the ongoing consolidation of the coal industry. In the Warrior Basin, a two-thirds drop in production, and hence emissions, from the very gassy Blue Creek No. 5 mine lowered estimated emissions by 100,000 metric tons. In Central Appalachia, the consolidation of the very gassy Island Creek mines after their acquisition by CONSOL reduced ventilation emissions by 120,000 metric tons. In the Western Basin, the closure of the Golden Eagle mine early in 1997 was responsible for additional decreases of 35,000 metric tons in methane emissions from ventilation systems and 20,000 metric tons in emissions from degasification systems.

Oil and Gas Production, Processing, and Distribution

U.S. Methane Emissions from Oil and Gas Production, Processing, and Distribution, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	6.2
Change Compared to 1996 (Million Metric Tons Methane)	0.1
Change from 1996 *(Percent)*	*1.0%*
Change Compared to 1990 (Million Metric Tons Methane)	0.5
Change from 1990 *(Percent)*	*8.1%*

Estimated methane emissions from U.S. oil and gas systems reached 6.16 million metric tons in 1997 (Table 17), more than 8 percent above 1990 levels. The steady growth in emissions from the oil and gas system can be traced to a general trend toward increased natural gas consumption between 1990 and 1997. During that period, total gas withdrawals grew by 12 percent, gas processed increased by 16 percent, and distribution main pipeline miles rose by 11 percent. About half the increase in emissions from 1990 to 1997 is attributable to the gas distribution system, which saw emissions rise from 1.36 million metric tons of methane in 1990 to 1.56 million metric tons in 1997. Emissions from gas production accounted for another one-third of the increase, growing from 1.47 million metric tons in 1990 to 1.59 million metric tons in 1997. Most of the remaining portion of the emissions escalation can be traced to emissions from gas processing, which grew from 650,000 metric tons in 1990 to 740,000 metric tons in 1997.[27] In contrast, emissions from transmission and storage remained stable, with a decline in transmission pipeline miles offset by increased withdrawals from gas storage. Methane emissions from oil wells dropped slightly between 1990 and 1997, but emissions from oil refining and transport rose by more than 8 percent during the period.

Stationary Combustion

U.S. methane emissions from stationary combustion in 1997 were 450,000 metric tons, well below the 1996 level of 593,000 metric tons and 22 percent lower than 1990 levels (Table 18). These declines are due primarily to a 27-percent drop in estimated consumption of wood in

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[25] U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*, EPA 430-R-97-020 (Washington, DC, September 1997).

[26] U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*, EPA 430-R-97-020 (Washington, DC, September 1997), pp. 3-7–3-8.

[27] The EPA estimates that the companies participating in the Natural Gas STAR program together avoided 142,000 metric tons of methane emissions in 1994, 185,000 metric tons in 1995, 208,000 metric tons in 1996, and 263,000 metric tons in 1997. Program participants report annually on emissions reductions achieved through such activities as equipment replacement, enhanced inspection and maintenance, and improved operations management. Participating companies may either use their own techniques to estimate reductions achieved or employ default values developed by the EPA and the Gas Research Institute.

Gas Vented

Previous editions of *Emissions of Greenhouse Gases in the United States* have included a line item for gas venting. The EIA collects data from State energy agencies on gas vented and flared. Gas venting may occur at several sites in the oil and gas system, including at the wellhead, at gas processing plants, during storage, and during transmission and distribution. Previously, EIA's emissions estimation method used the venting and flaring data and derived the portion vented on the basis of fractions estimated in a 1990 study by the U.S. Department of Energy.

In this year's report, EIA has employed a new method for estimating methane emissions from the oil and natural gas system, based on a study jointly funded by the EPA and the Gas Research Institute (GRI) (for detailed discussion of the new estimation method, see Appendix A). This method incorporates emissions factors and activity data that capture gas venting at each of the stages of the natural gas system. Thus, the inclusion of a separate line item for gas venting would result in significant double counting.

The revised estimation method does not, however, capture venting of associated gas at oil wells. If the flow of associated gas at an oil well is too small or intermittent to be of value or has an insufficient heat content to be marketed, or if there are not sufficient gathering pipeline and gas processing facilities in place, the gas will be vented or flared. Because State agencies do not report venting of associated gas separately, EIA is currently unable to provide an estimate of emissions from this source. The upper bound of emissions from this source is likely to be on the order of 500,000 metric tons.

U.S. Methane Emissions from Stationary Combustion, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	0.45
Change Compared to 1996 (Million Metric Tons Methane)	-0.14
Change from 1996 *(Percent)*	*-24.2%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.13
Change from 1990 *(Percent)*	*-21.8%*

*Less than 0.005 million metric tons.

the residential sector between 1996 and 1997, the result of an unusually warm winter in 1997 attributed to the "El Niño" effect. Residential wood consumption typically represents nearly 90 percent of all methane emissions from stationary combustion. Methane emissions are the result of incomplete combustion, and residential woodstoves and fireplaces provide much less efficient combustion than industrial or utility boilers. Thus, although the residential sector consumes about one-quarter the amount of wood that the industrial sector consumes, emissions from wood consumption for the residential sector are 29 times higher than those for the industrial sector.

Estimates of residential wood combustion are, however, highly uncertain (see Appendix C). The universe of wood consumers is large and heterogeneous, and wood for residential consumption is typically obtained from sources outside the documented economy. The EIA relies on the Residential Energy Consumption Survey (RECS) to estimate residential wood consumption. This survey includes only primary residences and thus systematically underestimates consumption by perhaps 5 percent. The last RECS was completed in 1993. Residential wood consumption since that time is estimated by scaling the 1993 number to heating degree days. Therefore, changes in estimated emissions are caused by changes in weather patterns.

Mobile Combustion

U.S. Methane Emissions from Mobile Combustion, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	0.24
Change Compared to 1996 (Million Metric Tons Methane)	-0.01
Change from 1996 *(Percent)*	*-3.3%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.01
Change from 1990 *(Percent)*	*-3.8%*

*Less than 0.005 million metric tons.

Methane emissions from mobile combustion in 1997 were estimated at 240,000 metric tons, down 8,000 metric tons from both 1990 and 1996 levels (Table 19).

Methane emissions from mobile sources declined slowly but steadily between 1980 and 1992, primarily because of a 27-percent decline in emissions from passenger cars. Catalytic converters, used on U.S. automobiles to control emissions, have grown more efficient in reducing methane emissions over time. Thus, as the U.S. fleet is replaced, the remaining automobiles have lower emissions profiles than their earlier counterparts. Emissions from passenger cars continued to decline between 1992 and 1995, dropping by another 16.9 percent. That decrease was more than offset, however, by an increase in emissions from the rapidly growing fleet of light-duty trucks, leading to a rise in overall emissions from mobile combustion between 1992 and 1995. In 1996 and 1997 the size of the light-duty truck fleet declined. In combination with continued declines in emissions from passenger cars, the decrease in emissions from light-duty trucks lowered emission levels by more than 5 percent between 1995 and 1997.

Waste Management

Waste management activities are the single largest source of U.S. anthropogenic methane emissions. In 1997, emissions from waste management were 10.4 million metric tons or 36 percent of total U.S. methane emissions. Emissions from waste management have declined from 11.1 million metric tons in 1990. Ninety-eight percent of emissions from waste management are attributed to emissions from landfills, and the remainder are associated with domestic wastewater treatment. The landfill share would be somewhat lower if reliable data on emissions from industrial wastewater treatment were available and were added to the total (see box on page 33). A diminishing portion of municipal solid waste is landfilled each year as recycling programs grow (Figure 5). Also, an increasing amount of methane generated from the decomposition of waste in landfills is being captured and used as an energy resource. Together, these trends have lowered emissions from landfills and waste management overall.

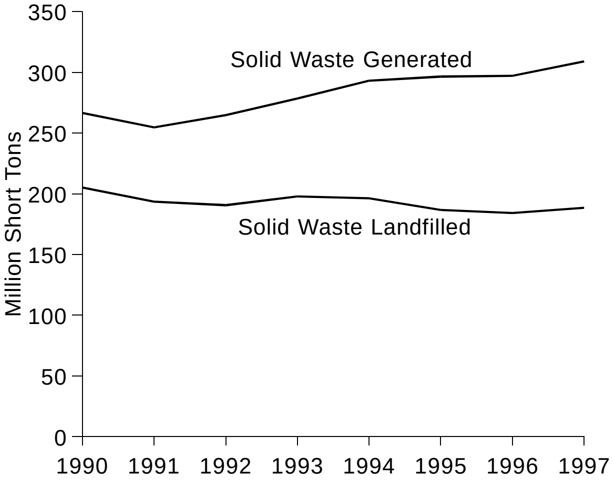
Landfills

U.S. Methane Emissions from Landfills, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	10.2
Change Compared to 1996 (Million Metric Tons Methane)	-0.2
Change from 1996 *(Percent)*	*-1.5%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.7
Change from 1990 *(Percent)*	*-6.8%*

Estimated methane emissions from U.S. landfills continued their seven-year decline from a 1990 peak of 11.0 million metric tons. In 1997, an estimated 10.2 million metric tons of methane were emitted from U.S. landfills, down 160,000 metric tons from the 1996 levels and 6.8 percent from the 1990 level (Table 20). While municipal solid waste generation continues to increase slowly (along the lines of population growth), the share of waste being recycled or incinerated rather than landfilled grew from 16 to 39 percent between 1990 and 1997.[28] Thus, gross methane generation at landfills grew slowly (less than 1 percent annually) between 1990 and 1995, stabilized in 1996 and declined in 1997.

Figure 5. U.S. Solid Waste Generated and Landfilled, 1990-1997



Source: *Biocycle*, "Nationwide Survey: The State of Garbage in America" (various years).

The estimated volume of methane recovery for flaring or energy use has nearly doubled since 1990. Absent the increase in methane recovery, net emissions of methane from U.S. landfills would have risen somewhat between 1990 and 1997. In 1990, approximately 940,000 metric tons of methane were recovered for energy use, and an additional 300,000 metric tons of methane were recovered and flared. By 1997, these

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[28] "Nationwide Survey: The State of Garbage in America, 1998," *Biocycle* (April 1998).

numbers had grown to an estimated 1.7 million metric tons and 667,000 metric tons respectively, preventing almost 2.4 million metric tons of potential methane emissions.

According to the EPA's Office of Solid Waste, municipal solid waste generation in the United States is expected to increase by about 4 percent between 1997 and 2000.[29] Per capita generation is expected to remain nearly unchanged, but a growing population will increase overall generation. The growth rate can be expected to bring the volume of waste generated in 2000 to approximately 340 million short tons. In contrast to waste generation, which is trending upward, the share of waste generated that will reach a landfill is expected to decline from 61 percent in 1997 to 55 percent in 2000. With waste combustion expected to remain stable as a share of waste generation at approximately 15 percent, predicted declines in landfilling are attributable to expected increases in curbside recycling.

The growth in methane recovery for energy between 1990 and 1997 was driven largely by the Federal Section 29 tax credit for alternative energy sources. This credit provides a subsidy roughly equivalent to 1 cent per kilowatthour for electricity generated using landfill gas. Signed contracts are currently in place for an additional 200 landfill gas-to-energy recovery projects. In order to qualify for Section 29 tax credits scheduled to run through 2008, the projects must have been in operational condition by June 30, 1998. If all the projects were fully operational at maximum capacity, the emissions reductions expected are estimated at an additional 1.8 million metric tons; however, the number of projects that actually met the deadline has not yet been determined.[30]

Increases in methane recovery and flaring after expiration of the Section 29 tax credits are expected to result from the implementation of the New Source Performance Standards (NSPS) and Emissions Guidelines administered by the EPA. These regulations require all landfills with more than 2.5 million metric tons of waste in place and annual emissions of nonmethane volatile organic compounds (NMVOCs) exceeding 50 metric tons to collect and burn their landfill gas, either by flaring or as an energy resource. In addition to the 600 landfills that currently flare gas, as many as 500 additional landfills could be required to flare gas under the NSPS and Emissions Guidelines regulations.[31] Those landfills with contracts in place that do not meet the June 30, 1998, operational deadline for Section 29 tax credits are likely to flare the gas, with significant additional emissions reductions beginning in 1999. Initial indications are that the majority of landfills potentially subject to the NSPS are able to demonstrate sufficiently low NMVOC emissions to be exempted.[32] Thus, a small number of additional flares are likely to come on line after 1999, further reducing methane emissions.

Domestic and Commercial Wastewater Treatment

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	0.16
Change Compared to 1996 (Million Metric Tons Methane)	*
Change from 1996 *(Percent)*	*0.9%*
Change Compared to 1990 (Million Metric Tons Methane)	0.01
Change from 1990 *(Percent)*	*7.3%*

* Less than 0.005 million metric tons.

Methane emissions from domestic and commercial wastewater treatment are a function of the share of organic matter in the wastewater stream and the conditions under which it decomposes. Wastewater may be treated aerobically or anaerobically. If it is treated aerobically, methane emissions will be low. Under anaerobic conditions, methane emissions will be high. There is little data available on wastewater treatment methods. Data on flaring or energy recovery from methane generated by wastewater is also sparse. Thus, emissions are scaled to U.S. population data. With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment

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[29] U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1996 Update,* EPA 530-S-96-001 (Washington, DC, May 1997), pp. 119-149.

[30] M. McGuigan, SCS Engineers, "GHG Emission Reductions From Landfill Gas Emissions," presented at the 21st Annual Landfill Gas Symposium (Austin, TX, March 23-26, 1998).

[31] M. McGuigan, SCS Engineers, "GHG Emission Reductions From Landfill Gas Emissions," presented at the 21st Annual Landfill Gas Symposium (Austin, TX, March 23-26, 1998).

[32] L. Albert, SCS Engineers, "New Source Performance Standards for Municipal Solid Waste Landfills—Two Years Experience," presented at the 21st Annual Landfill Gas Symposium (Austin, TX, March 23-26, 1998).

Industrial Wastewater Treatment

Methane emissions from industrial wastewater treatment are believed to be a function of the volume of wastewater generated, the organic content of the wastewater, and the method used to treat the wastewater. Methane emissions will be much more substantial if the wastewater is treated anaerobically (in the absence of oxygen) than if it is treated aerobically. Because data on volumes of wastewater generated by industry and the methods for treating that wastewater are limited, the EIA does not present estimates of methane emissions from industrial wastewater.

There are however, ongoing research efforts to characterize the volume of wastewater generated by key industries, its organic content, and the typical methods of treatment. In September 1997, the EPA's Office of Research and Development published *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*. This report provides emissions factors based on field tests at three meat processing plants, theoretical models, and empirical industrial digester data. Wastewater generation, organic content, and share of wastewater treated anaerobically were assumed on the basis of a broad literature search.

Using these parameters, estimated U.S. annual methane emissions from industrial wastewater would be on the order of 500,000 metric tons. There is, however, anecdotal evidence that very little industrial wastewater is treated anaerobically. Further, when industrial wastewater is treated anaerobically, the methane generated may be flared or recovered for energy use. Thus, 500,000 metric tons is likely to be at the high end of the emissions estimate range.

are estimated to have grown by less than 1 percent between 1996 and 1997 and by just over 7 percent since 1990.

Agricultural Sources

Agricultural activities represent another important U.S. source of anthropogenic methane. Emissions from agriculture totaled 8.6 million metric tons in 1997, nearly 30 percent of all U.S. methane emissions (Table 15). This share of emissions has risen from 27 percent in 1990, largely because of significant drops in emissions from both energy sources and waste management practices.

More than 94 percent of all methane emissions from agriculture are associated with livestock management. Almost two-thirds of emissions from livestock management can be traced to enteric fermentation, a process in which the digestion of carbohydrates in the forestomach of ruminant animals produces methane. Because cattle are the source of 95 percent of enteric fermentation emissions and 44 percent of emissions from animal waste, cattle populations are responsible for 75 percent of all emissions from agriculture and more than 22 percent of all U.S. anthropogenic methane emissions. Cattle populations grew between 1990 and 1994, raising methane emissions, then stabilized in 1995 and declined in 1996 and 1997. This decline was offset by a rapid rise in swine populations and an escalating concentration of swine on large industrial farms. Cattle population data back to 1980 suggest a cyclical pattern related to market conditions for cattle products. If livestock management practices remain unchanged, this pattern would suggest further declines in methane emissions from livestock over the next several years.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	5.4
Change Compared to 1996 (Million Metric Tons Methane)	-0.1
Change from 1996 *(Percent)*	*-1.9%*
Change Compared to 1990 (Million Metric Tons Methane)	0.2
Change from 1990 *(Percent)*	*3.8%*

Estimated methane emissions from enteric fermentation in domesticated animals were 5.4 million metric tons in 1997, 110,000 metric tons below estimates for 1996 and nearly 5 percent below peak levels in 1994 and 1995 (Table 21). After escalating from 1990 through 1995, emissions from enteric fermentation have declined to their lowest levels since 1991. Because cattle represent more than 95 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. Between 1990 and 1994, cattle populations grew, but by 1995 they had largely stabilized and in 1996 and 1997 populations decreased. Similarly, those variables that affect animal energy intake requirements, such as animal size and milk production, increased between 1990 and 1994 before declining from 1995 through 1997. Because methane emissions are a function of energy intake, emission trends attached to population changes have been exacerbated by simultaneous changes in energy intake requirements. For example, roughly two-thirds of the decline in emissions between 1996 and 1997 is attributable to decreased population and one-third to decreased energy intake requirements.

For the first time in preparing estimates of methane emissions from enteric fermentation for *Emissions of Greenhouse Gases in the United States*, the EIA has used State-level dairy population data in conjunction with regional emissions factors rather than national populations and national average emissions factors. This change was made to capture regional variations in feed intake and cattle energy requirements. The effect of the change on the estimates presented has been to raise estimates by 200,000 to 600,000 metric tons annually between 1995 and 1997.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	2.8
Change Compared to 1996 (Million Metric Tons Methane)	0.1
Change from 1996 *(Percent)*	*3.4%*
Change Compared to 1990 (Million Metric Tons Methane)	0.2
Change from 1990 *(Percent)*	*7.8%*

Estimated methane emissions from the solid waste of domesticated animals were 2.8 million metric tons in 1997, up from 2.7 million metric tons in 1996. Emissions levels remain well above the 1990 level of 2.6 million metric tons (Table 22). The 1997 growth in emissions is attributable to large increases in swine waste, particularly from swine bred for market, and the shift of swine populations to large industrial farms that employ concentrated manure management techniques. In 1997, methane emissions from swine waste reached the highest levels in the past 17 years. In contrast to emissions from enteric fermentation, which are nearly all attributable to cattle, 49 percent of emissions from the solid waste of domesticated animals were attributable to swine waste in 1997 and only 44 percent to cattle waste. Populations of swine bred for market grew by 9 percent between 1996 and 1997. Absent this rapid growth, overall emissions would have shown a slight decline as cattle populations and related emissions dropped in 1997.

Nearly three-fifths of the increase in emissions from solid waste between 1990 and 1997 can be credited to increased emissions from swine waste. About half the remainder is the result of increased emissions from cattle waste. The last portion of emissions growth is associated with increased poultry populations. Emissions from poultry waste accounted for just 7 percent of all emissions from this source in 1997, but they have increased by 26 percent since 1990.

Rice Cultivation

Estimated methane emissions from rice cultivation were 426,000 metric tons in 1997, up from the 403,000 metric tons in both 1996 and 1990 (Table 23). The increase would have been even larger with the addition of emissions from Florida, which were included for 1990-1996 but excluded for 1997 due to a lack of available data; however, Florida contributes less than 1,000 metric tons annually to national emissions levels.

Methane emissions from rice cultivation are, in part, a function of the area of land harvested. In 1996, the area harvested dropped to its lowest level since 1990. In 1997, the area of land harvested rebounded, increasing in 5 out of 7 rice-growing States (Arkansas, California, Louisiana, Mississippi, and Missouri). Area harvested, and thus emissions, rose by 17 percent in Arkansas alone. Only Texas reported a decline in area harvested. The overall area harvested in 1997 was more than 6 percent greater than in 1996 and 4.4 percent greater than in 1990.

Burning of Crop Residues

In 1997, fueled by large increases in corn, soybean, and pea production, methane emissions from the burning of crop residue grew to 41,500 metric tons, up by 6.1 percent from 1996 levels. This total was nearly 10 percent above the 1990 emissions of 37,900 metric tons. Nevertheless, this source accounts for less than 0.2 percent of total U.S. methane emissions.

Methane emissions from crop residue burning are a function of crop production and the share of crop residues burned. Overall, 1997 crop production was up by 4.3 percent from 1996 and by 12.0 percent from 1990. Emissions from the burning of crop residues in

California rice fields had decreased steadily from 1990 to 1996 as the share of residue burned declined from 99 percent to 50 percent. In 1997, however, a 13-percent increase in State production, accompanied by an end to reductions in the portion of crop residue burned, returned emissions from California rice fields to their 1995 levels.

Industrial Sources

U.S. Methane Emissions from Industrial Sources, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Methane)	0.13
Change Compared to 1996 (Million Metric Tons Methane)	*
Change from 1996 *(Percent)*	**
Change Compared to 1990 (Million Metric Tons Methane)	0.16
Change from 1990 *(Percent)*	*13.6%*

*Less than 0.005 million metric tons.
**Less than 0.05 percent.

Chemical Production

In 1997, Methane emissions from chemical production were unchanged from 1996 levels at 74,000 metric tons (Table 24). This was still 18,000 metric tons above 1990 levels. Since 1990, emissions levels have increased along with production levels as a consequence of steady economic growth. Production of styrene has grown the most markedly, rising by 42 percent between 1990 and 1997. Because ethylene is a principal feedstock of styrene, its production has increased similarly, jumping 32 percent.

Iron and Steel Production

Emissions from iron and steel production were essentially unchanged from 1996 levels, with a minimal increase of 150 metric tons due to higher pig iron production (Table 24). The 1997 total was 4.8 percent below 1990 levels. Iron and steel production dropped by about 13 percent during 1991, recovered about three-quarters of that loss by 1994, and since then has remained virtually flat.

Table 15. U.S. Methane Emissions from Anthropogenic Sources, 1990-1997
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Energy Sources								
Coal Mining	4.26	4.12	3.97	3.34	3.36	3.43	2.95	3.14
Oil and Gas	5.70	5.92	5.99	5.97	5.99	6.08	6.10	6.16
Stationary Combustion	0.57	0.60	0.63	0.55	0.54	0.59	0.59	0.45
Mobile Sources	0.25	0.24	0.24	0.24	0.25	0.26	0.25	0.24
Total Energy Sources	10.79	10.88	10.83	10.11	10.13	10.36	9.89	9.99
Waste Management								
Landfills	10.96	10.85	10.74	10.67	10.59	10.50	10.38	10.22
Wastewater Treatment	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16
Total Waste Management	11.11	11.00	10.89	10.82	10.75	10.66	10.54	10.38
Agricultural Sources								
Ruminant Animals	5.17	5.30	5.39	5.47	5.62	5.62	5.47	5.36
Animal Waste	2.57	2.67	2.69	2.71	2.77	2.77	2.68	2.77
Rice Paddies	0.40	0.39	0.44	0.40	0.47	0.44	0.40	0.43
Crop Residue Burning	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04
Total Agricultural Sources	8.18	8.40	8.56	8.62	8.90	8.86	8.59	8.60
Industrial Processes	0.12	0.11	0.12	0.12	0.13	0.13	0.13	0.13
Total	**30.20**	**30.39**	**30.41**	**29.68**	**29.91**	**30.02**	**29.15**	**29.11**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter. Crop residue burning—U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.83-4.84, web site www.iea.org/ipcc/invs6.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Table 16. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-1997
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Surface Mining								
Mining	0.43	0.42	0.42	0.42	0.45	0.45	0.46	0.47
Post-Mining	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Underground Mining								
Ventilation (Gassy Mines)	2.13	2.04	2.10	1.82	1.85	1.91	1.71	1.84
Ventilation (Nongassy Mines)	0.03	0.03	0.02	0.02	0.03	0.03	0.04	0.04
Degasification	1.26	1.23	1.17	1.05	1.06	1.21	1.02	1.06
Post-Mining	0.64	0.61	0.61	0.53	0.60	0.60	0.62	0.63
Methane Recovery for Energy (-)	0.25	0.25	0.39	0.53	0.67	0.80	0.94	0.94
Net Emissions	**4.26**	**4.12**	**3.97**	**3.34**	**3.36**	**3.43**	**2.95**	**3.14**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Coal production numbers from Energy Information Administration, *Coal Production,* DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584(94) and (95) (Washington, DC, 1994 and 1995). Methane recovery rates from U.S Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), pp. 3-19–3-24; and U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997). Ventilation data for 1985, 1988, 1990, and 1993 provided by G. Finfinger, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994 and 1996 provided by U.S. Environmental Protection Agency, Atmospheric Pollution Prevention Division, Coalbed Methane Outreach Program.

Table 17. U.S. Methane Emissions from Oil and Gas Operations, 1990-1997
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	P1997
Natural Gas Systems								
Production	1.47	1.49	1.49	1.51	1.55	1.57	1.58	1.59
Processing	0.65	0.71	0.70	0.71	0.71	0.72	0.73	0.74
Transmission and Storage	2.10	2.21	2.23	2.15	2.11	2.14	2.11	2.13
Distribution	1.36	1.39	1.44	1.48	1.49	1.52	1.55	1.56
Total	**5.58**	**5.80**	**5.86**	**5.85**	**5.86**	**5.95**	**5.97**	**6.03**
Oil Wells	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Oil Refining and Transportation	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09
Total	**5.70**	**5.92**	**5.99**	**5.97**	**5.99**	**6.08**	**6.10**	**6.16**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), Appendix A; *World Oil* (February issue, various years); American Gas Association, *Gas Facts* (various years); Energy Information Administration, *Natural Gas Annual,* DOE/EIA-0131 (various years); Radian Corporation, *Global Emissions of Methane from Petroleum Sources* (February 1992); Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 18. U.S. Methane Emissions from Stationary Combustion Sources, 1990-1997
(Thousand Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Residential								
Coal	*	*	*	*	*	*	*	*
Distillate Fuel	4	4	5	5	5	5	5	5
Natural Gas	5	5	5	5	5	5	6	5
LPG	*	1	*	1	1	1	1	1
Wood	512	541	569	483	474	526	525	382
Total	**522**	**550**	**579**	**494**	**484**	**536**	**536**	**393**
Commercial								
Coal	1	1	1	1	1	1	1	1
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	3	4	4	4	4	4	4	4
LPG	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*
Total	**5**	**6**	**6**	**6**	**6**	**6**	**6**	**6**
Industrial								
Coal	7	7	6	6	6	6	6	6
Fuel Oil	1	1	1	2	1	1	1	1
Natural Gas	13	13	13	14	14	15	15	15
LPG	2	3	3	3	3	3	3	3
Wood	13	12	13	13	13	13	13	13
Total	**36**	**35**	**37**	**37**	**38**	**38**	**39**	**38**
Electric Utility								
Coal	10	10	10	11	11	11	11	12
Fuel Oil	1	1	1	1	1	*	*	1
Natural Gas	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*
Total	**11**	**11**	**11**	**12**	**12**	**12**	**12**	**13**
Total All Fuels								
Coal	18	18	18	18	18	18	18	19
Fuel Oil	7	7	7	8	7	7	7	7
Natural Gas	21	22	22	23	24	24	25	25
LPG	3	3	3	3	3	4	4	4
Wood	525	553	582	497	487	539	539	395
Total	**575**	**603**	**632**	**549**	**540**	**592**	**593**	**450**

*Less than 500 metric tons of methane.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, web site www.epa.gov/ttn/chief; Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); *Monthly Energy Review*, DOE/EIA-0035(98/07) (Washington, DC, July 1998); and *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), p. 267.

Table 19. U.S. Methane Emissions from Mobile Sources, 1990-1997
(Thousand Metric Tons of Methane)

Item	1990	1991	1992	1993	1994	1995	1996	P1997
Motor Vehicles								
Passenger Cars	141	132	131	126	117	109	107	104
Buses	1	1	1	1	1	1	1	1
Motorcycles	4	4	4	4	4	4	4	4
Light-Duty Trucks	63	63	63	75	84	99	94	89
Other Trucks	12	12	12	13	14	14	15	15
Total	**222**	**211**	**211**	**218**	**220**	**228**	**220**	**213**
Other Transport	28	28	29	27	27	28	28	27
Total Transport	**249**	**239**	**240**	**245**	**247**	**255**	**248**	**240**

P = preliminary data.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics*, various years, Table VM-1. Vehicle emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.65-1.75, web site www.iea.org/ipcc/invs6.htm. Distribution of passenger car and light duty truck fleet model years for 1983, 1985, 1988, 1991, and 1994 according to data in the Energy Information Administration's "Residential Transportation Energy Consumption Surveys" for those years. Distribution for passenger cars and light duty trucks in other years computed by interpolation. Distribution of bus and other truck fleet according to model year computed assuming 10-percent attrition per annum of pre-1983 fleet for each year after 1984.

Table 20. U.S. Methane Emissions from Landfills, 1990-1997
(Million Metric Tons of Methane)

Type	1990	1991	1992	1993	1994	1995	1996	1997
Gross Emissions	12.2	12.3	12.4	12.5	12.6	12.6	12.6	12.6
Methane Recovery (Energy)	0.9	1.1	1.2	1.3	1.4	1.5	1.6	1.7
Methane Assumed Flared	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7
Net Emissions	**11.0**	**10.9**	**10.7**	**10.7**	**10.6**	**10.5**	**10.4**	**10.2**

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Sources: Municipal solid waste landfilled from *Biocycle*, "Nationwide Survey: The State of Garbage in America" (1989-1996). Emissions calculations based on S.A. Thorneloe et al., "Estimate of Methane Emissions from U.S. Landfills," Prepared for the U.S. Environmental Protection Agency, Office of Research and Development, in departmental review (April 1994), and D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environmental Change* (December 1992), pp. 311-328. Methane recovered and flared from S.A. Thorneloe, "Landfill Gas Recovery Utilization—Options and Economics," presented at the Sixteenth Annual Conference by the Institute of Gas Technology on Energy from Biomass and Wastes, Orlando, Florida (March 5, 1992); J. Pacey, "Methane Recovery from Landfills," presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, Washington, DC (June 27-29, 1995); and M. McGuigan, SCS Engineers, "GHG Emission Reductions From Landfill Gas Emissions," presented at the 21st Annual Landfill Gas Symposium (Austin, TX, March 23-26, 1998).

Table 21. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1997
(Million Metric Tons of Methane)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997
Cattle	4.88	5.01	5.11	5.19	5.35	5.36	5.22	5.12
Sheep	0.15	0.15	0.14	0.14	0.13	0.12	0.11	0.10
Pigs	0.08	0.09	0.09	0.09	0.09	0.09	0.08	0.09
Goats	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Horses	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03
Total	**5.17**	**5.30**	**5.39**	**5.47**	**5.62**	**5.62**	**5.47**	**5.36**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Cattle, sheep, and pig population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Goat and horse population figures extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, and 1992. Emissions calculations based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), pp. 159-161, web site www.epa.gov/globalwarming/inventory/1998-inv.html; and P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), pp. 271-284.

Table 22. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-1997
(Thousand Metric Tons of Methane)

Type of Animal	1990	1991	1992	1993	1994	1995	1996	1997
Cattle	**1,163**	**1,184**	**1,196**	**1,208**	**1,230**	**1,232**	**1,216**	**1,205**
Beef Cattle	249	264	271	278	288	287	277	272
Dairy Cattle	914	920	924	930	943	945	939	933
Swine	**1,234**	**1,306**	**1,312**	**1,308**	**1,343**	**1,338**	**1,259**	**1,357**
Market Swine	861	912	924	918	958	952	895	976
Breeding Swine	373	394	388	390	385	387	364	381
Poultry	**157**	**161**	**167**	**179**	**184**	**189**	**193**	**197**
Caged Layers	83	84	86	88	89	89	91	92
Broilers	73	77	81	91	95	100	102	105
Other Animals	**18**	**17**	**17**	**16**	**15**	**15**	**14**	**13**
Sheep	5	5	5	5	4	4	4	4
Goats	1	1	1	1	1	1	1	1
Horses	12	11	11	11	10	10	9	9
Total	**2,571**	**2,669**	**2,692**	**2,711**	**2,772**	**2,774**	**2,681**	**2,772**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Population data for horses and goats extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, and 1992. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), p. 6-8. Cattle sizes adjusted by annual slaughter weight from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Maximum methane production, and waste management systems used from L.M. Safley, M.E. Casada, et al., *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), pp. 24-27, and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1994*, EPA-230-496-006 (Washington, DC, November 1995), Appendix D. General methane conversion factors from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.25, web site www.iea.org/ipcc/invs6.htm. State methane conversion factors for dairy cattle from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), pp. 162-164, web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Table 23. Area of Land Harvested for Rice and Estimated U.S. Methane Emissions from Flooded Rice Fields, 1990-1997

Item	1990	1991	1992	1993	1994	1995	1996	1997
Area Harvested (Thousand Hectares) . . .	1,274	1,254	1,394	1,255	1,469	1,368	1,242	1,319
Methane Emissions-Low Estimate (Thousand Metric Tons)	128	125	140	128	149	139	128	136
Methane Emissions-High Estimate (Thousand Metric Tons)	679	664	740	676	787	735	678	718

Source: Rice area harvested data from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* annual reports. Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.53-4.70, web site www.iea.org/ipcc/invs6.htm.

Table 24. U.S. Methane Emissions from Industrial Processes, 1990-1997
(Thousand Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	P1997
Chemical Production								
Ethylene	17	18	18	19	22	21	22	22
Ethylene Dichloride	3	2	3	3	3	3	3	4
Styrene	15	15	16	18	20	21	22	21
Methanol	8	8	7	10	10	10	10	11
Carbon Black	14	13	15	16	16	17	17	17
Total	**56**	**57**	**60**	**66**	**72**	**72**	**74**	**74**
Iron and Steel Production								
Coke[a]	11	9	9	9	8	9	8	8
Sinter	6	5	6	6	6	6	6	6
Pig Iron	45	40	43	43	44	46	44	45
Total	**62**	**54**	**57**	**58**	**59**	**61**	**59**	**59**
Total Industrial Processes	**117**	**111**	**117**	**124**	**131**	**133**	**133**	**133**

[a] Based on total U.S. production of metallurgical coke, including non-iron and steel uses.

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years); Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years), p. 223; and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.iea.org/ipcc/invs6.htm.

4. Nitrous Oxide Emissions

Overview

U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1997

	Nitrous Oxide	Carbon Equivalent
Estimated 1997 Emissions (Million Metric Tons)	1.011	85.5
Change Compared to 1996 (Million Metric Tons)	-0.010	-0.8
Change from 1996 *(Percent)*	*-1.0%*	*-1.0%*
Change Compared to 1990 (Million Metric Tons)	0.047	3.9
Change from 1990 *(Percent)*	*4.8%*	*4.8%*

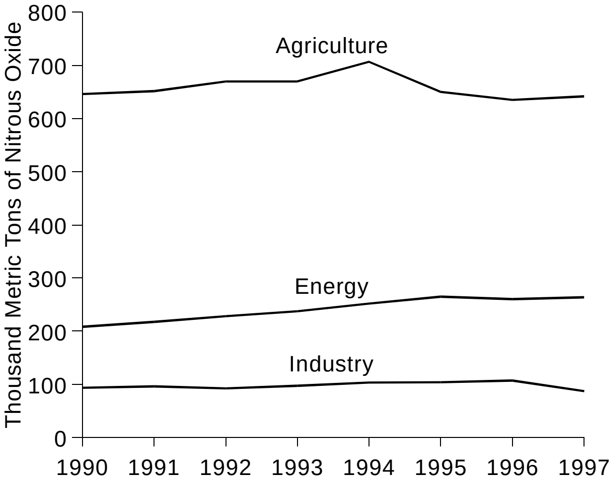
With a 100-year global warming potential (GWP) of 310, nitrous oxide is a significant contributor to atmospheric warming. Although there are many known natural and anthropogenic sources, emissions of nitrous oxide have been difficult to quantify, primarily because it has been one of the least studied greenhouse gases. Estimated U.S. anthropogenic nitrous oxide emissions totaled 1.0 million metric tons in 1997, down slightly from 1996 emissions levels but still 47,000 metric tons above 1990 levels (Table 25).

Nearly all the increase from 1990 levels can be attributed to emissions from mobile combustion, which grew by more than 30 percent between 1990 and 1995. Emissions stabilized from 1995 through 1997, as growth in the light-duty truck fleet slowed and the next generation of lower-emitting catalytic converters was introduced. These trends can be expected to lead to lower emissions from mobile combustion over the next few years.

Agricultural activities are the largest source of U.S. anthropogenic nitrous oxide emissions—primarily, the application of nitrogen to agricultural soils. Small quantities of nitrous oxide are also released from the burning of crop residues. Estimated emissions of nitrous oxide from agricultural sources were 642,000 metric tons in 1997, equal to 1990 levels and 7,000 metric tons (1.0 percent) higher than in 1996 (Figure 6). There are, however, large uncertainties connected with the emissions consequences of adding nitrogen to agricultural soils (see box on page 44).

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses,

Figure 6. U.S. Emissions of Nitrous Oxide by Source, 1990-1997



Source: Estimates presented in this chapter.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1997

Source	Thousand Metric Tons Nitrous Oxide 1990	Thousand Metric Tons Nitrous Oxide 1997	*Percent Change* 1990-1997	*Percent Change* 1996-1997
Energy Use	208	264	*26.7%*	*1.4%*
Agriculture	646	642	*-0.7%*	*1.0%*
Industrial	94	87	*-6.7%*	*-18.6%*

Revised Estimation Methods Produce Higher Estimates of U.S. Nitrous Oxide Emissions

This edition of *Emissions of Greenhouse Gases in the United States* provides annual estimates of U.S. nitrous oxide emissions that are more than twice as large as those in previous editions. The additional 600,000 metric tons of nitrous oxide are equivalent to roughly 49 million metric tons of carbon or about 3 percent of all U.S. greenhouse gas emissions. The increase is due principally to revised methods for estimating emissions from the application of nitrogen to agricultural soils. Revised emissions factors for mobile sources and the inclusion of three new sources—solid waste of domesticated animals (230,000 metric tons), waste combustion, and human sewage in wastewater—also contributed to the increase in estimated nitrous oxide emissions (see Appendix A for discussion of the methods used).

Previously, the method for estimating emissions from nitrogen fertilization included only direct emissions from the use of commercial synthetic fertilizers, which totaled just 160,000 metric tons in 1990. The revised method also includes direct emissions from the application of animal manure, direct emissions from crop residues, and direct emissions from soil mineralization. In addition, the estimated emissions total for fertilizers now also includes indirect emissions from leaching and atmospheric deposition (see Table 28). These additions result in an additional 260,000 metric tons of nitrous oxide emissions.

Estimates of emissions from fertilizer use are highly uncertain. Models used for estimation are based on limited sources of experimental data. The uncertainty increases when moving from emissions associated with animal manure to soil mineralization and atmospheric deposition, where both estimating emissions and partitioning emissions between anthropogenic and biogenic sources becomes increasingly difficult.

The revised method for mobile combustion includes updated emissions factors derived from recent vehicle testing performed by the U.S. Environmental Protection Agency's Office of Mobile Sources. The new method increased emissions estimates for this source by about 50 percent and added approximately 70,000 metric tons to annual emissions totals. Despite revised emissions factors, estimates of nitrous oxide emissions from mobile combustion remain highly uncertain. The Office of Mobile Sources tested 23 vehicles under the Federal Test Program (FTP) procedures. The FTP may prove to be imperfectly representative of actual in-use emissions, and the small number of cars tested may not be representative of the actual emissions of the vehicle fleet. Further, factors not yet fully identified or understood (such as the sulfur content of gasoline) may have a significant influence on emissions.

motorcycles, and trucks and stationary source combustion from residential, industrial, and electric utility energy use. Energy use was responsible for the release of 264,000 metric tons of nitrous oxide in 1997, an increase of 4,000 metric tons (1.4 percent) over the 1996 level.

Industrial production of adipic acid and nitric acid, which releases nitrous oxide as a byproduct of the reactions that synthesize these chemicals, accounted for emissions of 87,000 metric tons of nitrous oxide in 1997, a decrease of 6,300 metric tons (6.7 percent) from 1990 levels and a decrease of 20,000 metric tons (18.6 percent) from 1996 levels.

Energy Use

Nitrous oxide emissions from both mobile and stationary sources are byproducts of fuel combustion. Estimated 1997 energy-related emissions were 264,000 metric tons, approximately 26 percent of total U.S. anthropogenic nitrous oxide emissions (Table 25). Emissions from energy use are dominated by mobile combustion (1997 estimated emissions of 222,000 metric tons).

U.S. Nitrous Oxide Emissions from Energy Use, 1990-1997

Estimated 1997 Emissions (Thousand Metric Tons Nitrous Oxide)	263.7
Change Compared to 1996 (Thousand Metric Tons Nitrous Oxide)	3.5
Change from 1996 *(Percent)*	*1.4%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	55.5
Change from 1990 *(Percent)*	*26.7%*

Mobile Combustion

Nitrous oxide emissions from motor vehicles are caused primarily by the conversion of pollutant nitrogen oxides (NO_2) into nitrous oxide (N_2O) by vehicle catalytic converters. The normal operating temperature of catalytic converters is high enough to cause the thermal decomposition of nitrous oxide. Consequently, it is probable that nitrous oxide emissions result primarily from "cold starts" of motor vehicles and from catalytic converters that are defective or operating under abnormal conditions. This implies that the primary determinant of the level of emissions is motor vehicle operating conditions; however, different types of catalytic converters appear to differ systematically in their emissions, and emissions probably vary with engine size. Consequently, emissions also depend on the "mix" of vehicle age and type on the road. The rising popularity of light-duty trucks (with larger engines) tends to raise emissions, while the penetration of the latest model three-way catalytic converters (in 1996 and later model cars) tends to reduce emissions.

In addition to emissions from passenger cars and light-duty trucks, emissions from air, rail, and water transportation sources and from farm and construction equipment are also included in the estimates. Overall nitrous oxide emissions from mobile source combustion in 1997 are estimated at 222,000 metric tons (Table 26). Approximately 92 percent of the emissions can be attributed to motor vehicles. The rapid growth in emissions between 1990 and 1995 is a function of increasing motor vehicle use, the shifting composition of the light-duty vehicle fleet toward light trucks, and the gradual replacement of low emitting pre-1983 vehicles in the fleet with higher emitting post-1983 vehicles. The shift to advanced three-way catalytic converters in 1996 and 1997 model year cars has stabilized emissions from this source.

Stationary Combustion

During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems are typically low. In 1997, estimated nitrous oxide emissions from stationary combustion sources increased modestly, by 900 metric tons over 1996 and by a larger 9.8 percent since 1990 (Table 27). Nearly all the emissions increase of almost 4,000 metric tons between 1990 and 1997 can be attributed to coal-fired electricity generation, which grew in response to the growing demand for electricity. Coal-fired combustion systems produced some three-quarters of the 1997 emissions, and electric utilities accounted for approximately two-thirds of all stationary combustion emissions.

Agriculture

U.S. Nitrous Oxide Emissions from Agriculture, 1990-1997

Estimated 1997 Emissions (Thousand Metric Tons Nitrous Oxide)	641.6
Change Compared to 1996 (Thousand Metric Tons Nitrous Oxide)	6.5
Change from 1996 *(Percent)*	*1.0%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-4.4
Change from 1990 *(Percent)*	*-0.7%*

On a global scale, agricultural practices contribute approximately 70 percent of anthropogenic nitrous oxide emissions.[33] Similarly, in the United States, agricultural activities were responsible for 63 percent of 1997 nitrous oxide emissions. About three-quarters of agricultural emissions are associated with the application of commercial and animal-manure-based fertilizers. Nearly all the remaining agricultural emissions can be traced to the management of the solid waste of domesticated animals. The disposal of crop residues by burning also produces nitrous oxide that is released into the atmosphere; however, the amount is relatively minor, at 1,850 metric tons or about 0.1 percent of total U.S. emissions of nitrous oxide from agricultural sources in 1997. Overall, emissions from agricultural activities were unchanged between 1990 and 1997.

Nitrogen Fertilization of Agricultural Soils

Nitrous oxide uptake and emissions occur naturally as a result of nitrification and denitrification processes in soil and crops. Nitrogen may be added to soil and crops through the application of commercial synthetic fertilizers or animal manure. When nitrogen-based fertilizers are added to the soil, emissions generally increase, unless application precisely matches plant

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[33] A.R. Mosier, "Nitrous Oxide Emissions from Agricultural Soils," in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), p. 277.

uptake and soil capture.[34] Nitrous oxide may be emitted directly to the atmosphere from fertilizers or from crop residues. It may also be emitted directly from nitrogen-rich soils, called histosols.

Nitrous oxide may also be released indirectly when nitrogen-enriched runoff reaches rivers and streams. Additional indirect emissions occur when a small portion of nitrogen from fertilizer application reaches the atmosphere in its elemental form and is converted to nitrous oxide. The EIA estimates that a total of 658,000 metric tons of nitrous oxide were released into the atmosphere as a result of direct and indirect emission associated with fertilization practices in 1997 (Table 28). This represents an increase of 5,000 metric tons (less than 1 percent) compared with the amount released in 1990 and a decrease of 7,000 metric tons (1.1 percent) compared with 1996.

Crop Residue Burning

Incomplete combustion of agricultural wastes during burning of crop residues produces various gases, including nitrous oxide. Estimated emissions of nitrous oxide from this source were approximately 1,600 metric tons in 1997, up by 8.3 percent from 1996 (Table 25). As with methane emissions from crop residue burning, emissions of nitrous oxide grew as a result of increased corn, soybean, and pea production. Although emissions from this source remain very small, at about 0.2 percent of all U.S. nitrous oxide emissions, they have grown by 20 percent since 1990.

The estimates of U.S. nitrous oxide emissions from the burning of crop residues presented in this report are roughly one-third of those published in the previous year's edition of *Emissions of Greenhouse Gases in the United States*. The downward revision is the result of a change in the assumed fraction of each crop burned, from 10 percent to 3 percent, as recommended by the U.S. Environmental Protection Agency (EPA) in its draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*. (For more detail on the method used in this report, see Appendix A.)

Solid Waste of Domesticated Animals

Nitrous oxide is released as part of the microbial denitrification of animal manure. The volume of nitrous oxide emissions is a function of animal size and manure production, the amount of nitrogen in the animal waste, and the method of managing the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content than does waste managed in anaerobic lagoon and liquid systems.

Estimated 1997 nitrous oxide emissions from animal waste were 235,000 metric tons, down by 1.7 percent from 1996 levels but still slightly higher than 1990 levels (Table 29). This makes animal waste the second-largest U.S. source of nitrous oxide emissions after the application of fertilizers. Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which represent approximately 95 percent of emissions from the solid waste of domesticated animals. Thus, emissions levels have largely moved in sync with cattle populations, growing between 1990 and 1994, stabilizing in 1995, and declining in 1996 and 1997.

Waste Management

U.S. Nitrous Oxide Emissions from Waste Management, 1990-1997

Estimated 1997 Emissions (Thousand Metric Tons Nitrous Oxide)	18.3
Change Compared to 1996 (Thousand Metric Tons Nitrous Oxide)	0.1
Change from 1996 *(Percent)*	*0.6%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	1.7
Change from 1990 *(Percent)*	*10.5%*

Nitrous oxide emissions from waste management account for almost 2 percent of all U.S. anthropogenic nitrous oxide emissions (Table 25). Emissions from human sewage in wastewater are responsible for more than 90 percent of the estimated emissions from this source, and the remainder are associated with waste combustion. Estimated emissions from waste management have grown slowly between 1990 and 1997 because estimates from human sewage in wastewater are partially scaled to population data. Because of the lack of reliable data and an effective estimation method, no estimate of emissions from industrial wastewater was calculated, leaving estimated emissions from waste management somewhat lower than they otherwise would have been.

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[34] A.F. Bouwman, "Exchange of Greenhouse Gases Between Terrestrial Ecosystems and the Atmosphere," in A.F. Bouwman (ed.), *Soils and the Greenhouse Effect* (New York, NY: John Wiley and Sons, 1990).

Waste Combustion

In 1997, estimated nitrous oxide emissions from waste combustion were 834 metric tons, down by more than 6 percent from 1996 levels and 9 percent below 1990 levels. The total volume of waste generated in the United States increased by 16 percent between 1990 and 1997. In 1990, the share of waste burned hit a high of 11.5 percent. After dropping to 10 percent in 1991, the share of waste that was incinerated in the United States remained relatively stable through 1996—in the neighborhood of 10 percent of all waste generated. Thus, increasing levels of waste generation led to an increase in the total volume of waste incinerated and higher nitrous oxide emissions. The share of waste incinerated dropped from 10 percent in 1996 to 9 percent in 1997 as the share of waste recycled increased, with a corresponding drop in the estimate of nitrous oxide emissions.

Human Sewage in Wastewater

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found in human or animal waste. It is produced by two natural processes: nitrification and denitrification. Nitrification, an aerobic process, converts ammonia into nitrate; denitrification, an anaerobic process, converts nitrate to nitrous oxide. Factors that influence the amount of nitrous oxide generated from wastewater include temperature, acidity, biochemical oxygen demand (BOD),[35] and nitrogen concentration.

In 1997, nitrous oxide emissions from wastewater were 17,400 metric tons, a 0.9-percent increase from 1996 levels and a 11.2-percent increase from the 1990 level (Table 25). Estimates of nitrous oxide emissions from human waste correspond to population size and per capita protein intake. In addition to slow but steady population growth, the U.S. per capita protein intake has risen by 3.7 percent since 1990, accounting for the rise in emissions.[36]

Industrial Processes

U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1997

Estimated 1997 Emissions (Thousand Metric Tons Nitrous Oxide)	87.4
Change Compared to 1996 (Thousand Metric Tons Nitrous Oxide)	-20.0
Change from 1996 *(Percent)*	*-18.6%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-6.3
Change from 1990 *(Percent)*	*-6.7%*

Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 30 provides estimates of emissions from the production of adipic acid and nitric acid, the two principal known sources. Emissions from the combination of these two processes have decreased by 6,300 metric tons (6.7 percent) since 1990 and by 20,000 metric tons (18.6 percent) since 1996. All the decline can be traced to decreased emissions from adipic acid production, which dropped as emissions controls were added to the third of four manufacturing plants currently in operation.

Industrial Wastewater Treatment

Nitrous oxide emissions from industrial wastewater treatment are the result of nitrification and denitrification, with denitrification having the largest effect. Denitrification is inhibited by the presence of oxygen. A carbon source is also required for denitrification.

Because there is limited data on volumes of wastewater generated and the methods for treating wastewater, the EIA does not present estimates of nitrous oxide emissions from industrial wastewater. There are however, ongoing research efforts to characterize the volume of wastewater generated by key industries and the typical methods of treatment.

In September 1997, the U.S. Environmental Protection Agency's Office of Research and Development published the report, *Estimates of Global Greenhouse Gas Emissions From Industrial and Domestic Wastewater Treatment*. The report provides nitrous oxide emissions factors for wastewater degrading under anaerobic conditions, based on field tests at three meat processing plants; however, it does not provide an overall national estimate of nitrous oxide emissions from industrial wastewater. There is anecdotal evidence that very little industrial wastewater is treated anaerobically, thus limiting the potential size of emissions from this source.

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[35] Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

[36] Food and Agriculture Organization of the United Nations, web site apps.fao.org/lim500/nph-wrap.pl.

Adipic Acid Production

Adipic acid is a fine, white powder that is used primarily in the manufacture of nylon fibers and plastics, such as carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes.

In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Nitrous oxide is an intrinsic byproduct of this chemical reaction. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.[37] Between 1990 and 1994 emissions from adipic acid manufacture grew slowly until they reached 60,000 metric tons (Table 30). After remaining relatively stable in 1995 and 1996, emissions dropped sharply to just 42,000 metric tons in 1997. Through 1996, two of the four plants that manufacture adipic acid controlled emissions by thermally decomposing the nitrous oxide. This technique eliminates 98 percent of potential emissions from the plants.[38] By mid-1997 a third plant had installed emissions controls, raising the share of production employing controls from 77 percent to 85.4 percent. With the controls in place for the full year in 1998, emissions from this source can be expected to fall further.[39]

Nitric Acid Production

Nitric acid, a primary ingredient in fertilizers, usually is manufactured by oxidizing ammonia (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation. Measurements at a DuPont plant indicate emissions factors of 2 to 9 grams of nitrous oxide per kilogram of nitric acid manufactured.

The 9.1 million tons of nitric acid manufactured in 1997 resulted in estimated emissions of 45,000 metric tons of nitrous oxide (Table 30). There is, however, a considerable degree of uncertainty associated with this estimate, because the emissions factor for the DuPont plant may not in fact be representative of the entire industry (see Appendix A).

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[37] M.H. Thiemens and W.C. Trogler, “Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide,” *Science*, Vol. 251, No. 4996 (February 1991).

[38] Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

[39] R.A. Reimer, R.A. Parrett, and C.S. Slaten, “Abatement of N_2O Emissions Produced in Adipic Acid,” in *Proceedings of the Fifth International Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, July 1992).

Table 25. Estimated U.S. Emissions of Nitrous Oxide, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Agriculture								
Nitrogen Fertilization of Soils	416	419	435	431	464	406	395	405
Crop Residue Burning	1	1	2	1	2	1	2	2
Solid Waste of Domesticated Animals	229	231	234	238	241	243	239	235
Total	**646**	**651**	**670**	**670**	**706**	**650**	**635**	**642**
Energy Use								
Mobile Sources	171	181	191	199	213	226	220	222
Stationary Combustion	38	37	37	38	39	39	40	41
Total	**208**	**218**	**228**	**237**	**252**	**265**	**260**	**264**
Waste Management								
Waste Combustion	1	1	1	1	1	1	1	1
Human Sewage in Wastewater	16	16	16	16	17	17	17	17
Industrial Sources	**94**	**96**	**93**	**98**	**103**	**104**	**107**	**87**
Total	**964**	**982**	**1,008**	**1,022**	**1,080**	**1,037**	**1,021**	**1,011**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Crop residue burning—U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.81-4.94, web site www.iea.org/ipcc/invs6.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html. Emissions from human sewage—Food and Agriculture Organization of the United Nations, web site, apps.fao.org/lim500/nph-wrap.pl; and U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998).

Table 26. U.S. Nitrous Oxide Emissions from Mobile Sources, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Item	1990	1991	1992	1993	1994	1995	1996	P1997
Motor Vehicles								
Passenger Cars	99	106	115	111	111	108	108	108
Buses	*	*	*	*	*	*	*	*
Motorcycles	*	*	*	*	*	*	*	*
Light-Duty Trucks	48	51	53	64	78	94	87	89
Other Trucks	6	6	6	6	7	7	7	8
Total	**154**	**164**	**174**	**182**	**196**	**209**	**202**	**205**
Other Mobile Sources	17	17	17	17	17	17	18	17
Total Mobile Sources	**171**	**181**	**191**	**199**	**213**	**226**	**220**	**222**

P = preliminary data.

*Less than 500 metric tons of nitrous oxide.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics* (various years), Table VM-1. Passenger car and light-duty truck emissions coefficients from U.S. Environmental Protection Agency, Office of Air and Radiation, *Emissions of Nitrous Oxide From Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996*, EPA-420-R-98-009 (Washington DC, August 1998). Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.64-1.68, web site www.iea.org/ipcc/invs6.htm.

Table 27. U.S. Nitrous Oxide Emissions from Stationary Combustion Sources, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Commercial	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	*	*	*	*	*	*	*	*
Fuel Oil	1	1	1	*	*	*	*	*
Natural Gas	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*
Residential	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**
Coal	*	*	*	*	*	*	*	*
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	*	*	1	1	1	1	1	1
Industrial	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
Coal	4	4	4	4	4	4	4	3
Fuel Oil	5	5	5	5	6	5	6	6
Natural Gas	1	1	1	1	1	1	1	1
Electric Utility	**25**	**25**	**25**	**26**	**26**	**26**	**27**	**28**
Coal	24	24	24	25	25	25	27	27
Fuel Oil	1	1	1	1	1	*	*	1
Natural Gas	*	*	*	*	*	*	*	*
Fuel Totals								
Coal	28	28	28	29	29	29	30	31
Fuel Oil	7	7	7	7	8	7	8	8
Natural Gas	2	2	2	2	2	2	2	2
Wood	*	*	*	*	*	*	*	*
Total (All Fuels)	**38**	**37**	**37**	**38**	**39**	**39**	**40**	**41**

*Less than 500 metric tons of nitrous oxide.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.50, web site www.iea.org/ipcc/invs6.htm. Energy consumption data from Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, October 1997); and *Monthly Energy Review*, DOE/EIA-0035(98/07) (Washington, DC, July 1998).

Table 28. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Direct Emissions								
Nitrogen Fertilizers	179	182	183	193	195	173	159	160
Animal Manure	6	6	6	6	6	6	6	6
Crop Residues	92	90	104	83	112	93	106	114
Soil Mineralization	7	7	7	7	7	7	7	7
Total	**284**	**285**	**300**	**290**	**321**	**279**	**278**	**287**
Indirect Emissions								
Soil Leaching	112	114	115	121	122	109	100	101
Atmospheric Deposition	19	20	20	21	21	19	17	17
Total	**132**	**134**	**135**	**142**	**143**	**128**	**118**	**118**
Total	**416**	**419**	**435**	**431**	**464**	**407**	**395**	**405**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.iea.org/ipcc/invs6.htm. Total nitrogen content of U.S. commercial fertilizer consumption—1988-1994, Tennessee Valley Authority; 1995-1996, Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, DC, 1995 and 1996). Manure application based on cattle population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Manure production and waste management systems used from L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, DC, February 1992), and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1994* (Washington, DC, November 1995).

Table 29. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Cattle	215	217	219	223	226	228	225	221
Swine	5	5	5	5	6	6	5	6
Poultry	3	3	3	4	4	4	4	4
Sheep	3	3	3	3	3	3	3	2
Goats	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1
Total	**229**	**231**	**234**	**238**	**241**	**243**	**239**	**235**

Notes: Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Nitrogen content of waste by species, manure management systems, and emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.iea.org/ipcc/invs6.htm. Animal populations from U.S. Department of Agriculture, National Agricultural Statistics Service, web site www.mannlib.usda.edu.

Table 30. U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1997
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Adipic Acid								
Controlled Sources	3	4	3	4	4	4	4	4
Uncontrolled Sources	51	53	49	53	56	56	58	38
Total	**54**	**57**	**52**	**56**	**60**	**60**	**61**	**42**
Nitric Acid	**40**	**40**	**41**	**41**	**43**	**44**	**46**	**45**
Total Known Industrial Sources	**94**	**96**	**93**	**98**	**103**	**104**	**107**	**87**

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Appendix A.

5. Halocarbons and Other Gases

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Carbon Equivalent)	37.5
Change Compared to 1996 (Million Metric Tons Carbon Equivalent)	2.9
Change from 1996 *(Percent)*	*8.3%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	15.2
Change from 1990 *(Percent)*	*68.3%*

Beyond the three principal gases that account for some 98 percent of GWP-weighted U.S. emissions (carbon dioxide, methane, and nitrous oxide), there are an array of gases that affect climate in diverse ways. Most are engineered chemicals that do not occur in nature. The consequences of their emissions for the climate are considerably less than those of the other greenhouse gases, for various reasons. In some cases, the quantities emitted are small; in other cases, the impact of a particular gas on the climate may be difficult to quantify or measure.

The Kyoto Protocol has crystallized these ambiguities by defining three classes of gases that "count" for emissions estimation: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). This chapter describes emissions sources and estimates emissions for HFCs, PFCs, and sulfur hexafluoride. Emissions are also estimated for two other categories of gases that *do not* "count" under the Kyoto Protocol but do have indirect and difficult-to-measure effects on climate:

- Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (sometimes called by their trade name, "halons"), which are ozone-depleting substances controlled under the Montreal Protocol
- Gases that indirectly affect climate through their effects on tropospheric ozone, which are controlled as "criteria pollutants" in the United States under the authority of the Clean Air Act.

As a group, emissions of HFCs, PFCs, and sulfur hexafluoride are rising rapidly. In the case of HFCs, the rapid rise in emissions reflects the introduction of HFCs specifically as replacements for CFCs, whose use is being phased out under the Montreal Protocol, because they damage the Earth's ozone layer. CFCs have been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with CFC production virtually ceasing by 1996, HFCs have been rushed into the market to fill the void in many key applications. Emissions of PFCs and perfluoropolyethers (PFPEs) have also been rising in the 1990s (although not as rapidly as HFC emissions), mainly because of the recent commercial introduction of new PFCs and PFPEs for use in various applications within the semiconductor manufacturing industry.

HFCs, PFCs, and sulfur hexafluoride are emitted in small quantities, but they have disproportionate effects because their long atmospheric lifetimes and extreme scarcity in the atmosphere give them extremely large global warming potentials (GWPs). Sulfur hexafluoride is the most potent of the greenhouse gases, with a GWP of 23,900. PFCs also tend to have particularly high GWPs, falling in the approximate range of 7,000 to 9,000. Among HFCs, HFC-23 is the most potent greenhouse gas, with a GWP of 11,700.

Table 31 summarizes U.S. emissions of halocarbons and other gases from 1990 to 1997, and Table 32 shows U.S. emissions of HFCs, PFCs, and sulfur hexafluoride in million metric tons carbon equivalent. As Table 32 indicates, throughout the 1990s HFC emissions have accounted for roughly one-half of the total carbon-equivalent emissions of HFCs, PFCs, and sulfur hexafluoride combined.

The emissions estimates presented in Tables 31 and 32 are taken primarily from a draft EPA report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998). This is a departure from the emissions estimates presented in past years, which for 1990, 1994, and 1995 were drawn from EPA and other sources and for other years were estimated by EIA. The new estimates presented this year differ from past estimates as a result of differences between the methodologies and data sources used in the new EPA report and those used by the EIA and by the EPA in earlier sources. For HFCs, PFCs, and sulfur hexafluoride, the total new emissions estimates (expressed on a GWP-weighted basis) range from 12 percent to 21 percent lower than the earlier estimates for the 1990-1995 period. More information on methodologies and data sources for emissions of halocarbons and related gases is presented in Appendix A.

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Carbon Equivalent)	20.8
Change Compared to 1996 (Million Metric Tons Carbon Equivalent)	2.7
Change from 1996 *(Percent)*	*15.0%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	11.0
Change from 1990 *(Percent)*	*112.3%*

HFCs are compounds containing carbon, hydrogen, and fluorine. They do not destroy ozone. The market for HFCs is expanding as CFCs are being phased out. It is difficult to keep pace with the variety of HFCs that are being developed and the quantities being produced. Consequently, accurate data are difficult to obtain.

HFC-23

Although emissions of HFC-23 are relatively small, its high GWP gives it a substantial direct effect. HFC-23 is created as a byproduct in the production of HCFC-22. Small amounts are also used in semiconductor manufacture.

Previously, HFC-23 emissions were estimated as being 2 to 4 percent of HCFC-22 production; however, the EPA has developed its most recent emissions estimates on the basis of actual measurements of feed components and HFC-23 process stream concentrations at HCFC-22 production plants. Using this approach, the EPA estimates 1996 HFC-23 emissions at 2,660 metric tons.[40] Annual emissions dropped by 22 percent between 1992 and 1995 before rebounding by 14 percent in 1996. Currently, demand for HCFC-22 as a chemical feedstock is growing at an annual rate of 7 percent, and HCFC-22 is continuing to make inroads in refrigeration applications as a replacement for CFCs.[41] The Climate Change Action Plan (CCAP) includes a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which may help to offset the impact of rising HCFC-22 demand in the short term. HCFC-22 production (except for use as a feedstock) is scheduled to be eliminated by 2020 under the Copenhagen Amendments.

1,2,2,2-Tetrafluoroethane (HFC-134a)

HFC-134a, with a GWP of 1,300, is gaining importance as a replacement for CFCs, especially in automotive air conditioners. Emissions in 1990 were estimated at only 500 metric tons, but they are growing rapidly. In 1993, Ford Motor Company sold nearly 40,000 vehicles, each of which used approximately 2 pounds of HFC-134a in its air conditioner.[42] Previous models used about 2.5 pounds of CFC-12. Nearly all 1994 and subsequent model year automobiles use HFC-134a as their air conditioner refrigerant. In addition, HFC-134a conversion packages are now available for older cars.

Automobile air conditioners are subject to leakage, with sufficient refrigerant leaking out (15 to 30 percent of the charge) over a 5-year period to require servicing. On its Form EIA-1605, General Motors (GM) reported total HFC-134a emissions of nearly 1,500 metric tons from GM-made vehicles on the road in 1996.[43] GM based this estimate on an assumed annual leakage rate of 10 percent per year. With GM vehicles accounting for about one-third of the U.S. light-duty fleet, the GM emissions estimate implies that total U.S. HFC-134a emissions from mobile air conditioners were equal to about 4,500 metric tons in 1996. Emissions from this source are expected to continue to increase in the near future, as the replacement of vehicles using CFCs proceeds at a rapid pace.

In addition to its use in all new automobiles, a significant automotive aftermarket for HFC-134a has been

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[40] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), pp. 66-67, web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[41] "Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

[42] Information obtained during spoken communication with Ford Motor Company representatives.

[43] Form EIA-1605 is a greenhouse gas emissions and emission reductions reporting form, which is submitted to EIA on a voluntary basis by entities interested in creating a public record of their emissions reduction activities.

developing. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997. A spokesman for Elf Atochem North America Inc. estimates that this number will grow to 10 million in 1998, as supplies of CFC-12 become tighter.[44]

HFC-134a is also used as a refrigerant in most new refrigerators built in the United States and in commercial chillers, but leakage from these sources is much less significant than that from automotive air conditioners. Leakage occurs primarily during servicing of the units rather than during normal operation. Short-term uses of HFC-134a, on the other hand, are becoming a significant source of emissions. Such uses include aerosols and open-cell foam blowing, which are denoted as short term because most of the HFC-134a used will be emitted to the atmosphere within a short period of time. According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a for short-term applications jumped almost fourfold between 1994 and 1995 before leveling off at 10,000 metric tons, or 12 percent of 1996 sales for all uses.[45] HFC-134a has the distinct competitive advantage of being the only nonflammable liquefied gas propellant available on the market.

1,1-Difluoroethane (HFC-152a)

As a non-ozone-depleting substance with a GWP of only 140, HFC-152a is an attractive potential replacement for CFCs. It can be used as a blowing agent, an ingredient in refrigerant blends (e.g., in R-500), and in fluoropolymer manufacturing applications. It is also compatible with the components used in aerosol products. Unlike CFCs, however, HFC-152a is flammable.

Only one company (DuPont) produces HFC-152a, using the trade name Dymel-152a. In 1995 the company reported having doubled its production capacity from 1992 levels, to 35 million pounds.[46] DuPont scientists believe that HFC-152a will capture the primary share of the propellant market, because it is less expensive than HFC-134a (the primary alternative), has a much lower GWP, and is a better solvent (an important characteristic if ingredients are to remain in solution).[47] DuPont probably was producing HFC-152a at nearly full capacity in 1994, corresponding to production of about 8,000 metric tons. The company reported 1994 HFC-152a emissions of 180 metric tons on its Form EIA-1605. In 1995, however, DuPont's reported emissions dropped to only 18 metric tons. The EPA estimated 1990 emissions of HFC-152a at 2,620 metric tons, dropping to only 310 metric tons in 1992, before climbing back to 1,080 metric tons in 1996.

Other HFCs

Other hydrofluorocarbons with considerable radiative forcing potential include HFC-125 (C_2HF_5), HFC-143a ($C_2H_3F_3$), HFC-227ea (C_3HF_7), and HFC-236fa ($C_3H_2F_6$), with 100-year GWPs of 2,800, 3,800, 2,900, and 6,300, respectively. Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs. For 1996, the EPA estimates emissions at 3,170 metric tons for HFC-125, 230 metric tons for HFC-143a, 2,060 metric tons for HFC-227ea, and 80 metric tons for HFC-236fa.

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Carbon Equivalent)	7.4
Change Compared to 1996 (Million Metric Tons Carbon Equivalent)	0.2
Change from 1996 *(Percent)*	*2.2%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	2.2
Change from 1990 *(Percent)*	*42.3%*

Perfluorocarbons are compounds composed of carbon and fluorine. PFC emissions are not regulated or reported, although their high GWPs (6,900 for perfluoromethane and 9,200 for perfluoroethane) have drawn the attention of the CCAP. PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike HFCs, they are essentially permanent additions to the atmosphere. As byproducts of aluminum production, they arise during discrete

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[44] "Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

[45] Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1996* (Washington, DC, January 1998), p. 8.

[46] "DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product," *Ozone Depletion Online Today* (Alexandria, VA, June 9, 1995).

[47] "DuPont Chemist Sees HFC-152a as Most Viable Ozone-Safe Aerosol Propellant Candidate," *Spray Technology & Marketing* (December 1994), p. 38; and "DuPont Scientist Says HFC-152a Offers Ozone-Safe, VOC-Free Option for Aerosol Industry," *Spray Technology & Marketing* (April 1995).

periods of process inefficiency. Emissions can be reduced by improving process efficiency. The Voluntary Aluminum Industrial Partnership, aimed at reducing PFC emissions from the aluminum industry, is a CCAP initiative.

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting. The EPA estimates that 0.6 kilogram of perfluoromethane (CF_4, also known as carbon tetrafluoride) and 0.06 kilogram of perfluoroethane (C_2F_6) are emitted as a result of each metric ton of aluminum smelted.[48] These coefficients, in conjunction with aluminum production figures, suggest U.S. emissions of 2,160 metric tons of perfluoromethane and 216 metric tons of perfluoroethane in 1997. U.S. primary aluminum production has been increasing since 1994, and the trend is expected to continue as the automobile industry expands its use of aluminum.[49]

Another source of PFC emissions is semiconductor manufacturing. Perfluoromethane and perfluoroethane are used as etchants and cleaning agents in semiconductor manufacturing. Although anywhere from 5 to 95 percent of the CF_4 and C_2F_6 is destroyed, the process produces fugitive emissions of perfluoroethane, perfluoromethane, and sulfur hexafluoride. The United States consumed an estimated 800 tons of perfluoroethane and perfluoromethane in 1995.[50] The EPA's Atmospheric Pollution Prevention Division believes that emissions of PFCs, HFC-23, and sulfur hexafluoride from the semiconductor industry totaled about 1 million metric tons carbon equivalent in 1994, with about 60 to 70 percent of GWP-weighted emissions consisting of perfluoroethane.[51] This is equivalent to emissions of about 70 metric tons of perfluoroethane and smaller amounts of the other gases. For 1996, the EPA estimates total emissions of all greenhouse gases from semiconductor manufacturing at 1.4 million metric tons carbon equivalent.[52]

It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued rapid expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, industry efforts to curb emissions may help to offset these market forces at least partially. Since 1992, DuPont—the sole manufacturer of perfluoroethane—has been asking its customers to limit PFC use.[53] A number of semiconductor manufacturing firms have joined an EPA program to reduce PFC emissions voluntarily.[54] In addition, a number of PFC distributors are developing PFC emissions control equipment.[55] Recycling, abatement, and other control options remain in the early stages of development, however, and PFC substitutes are not yet available.[56]

A variety of other perfluorinated compounds are beginning to be used in the semiconductor industry, including C_3F_8 (manufactured by 3M), C_4F_{10} (with a GWP of 7,000), C_6F_{14} (with a GWP of 7,400), NF_3 (manufactured by Air Products), and CHF_3.

Sulfur Hexafluoride

U.S. Emissions of Sulfur Hexafluoride, 1990-1997

Estimated 1997 Emissions (Million Metric Tons Carbon Equivalent)	9.3
Change Compared to 1996 (Million Metric Tons Carbon Equivalent)	*
Change from 1996 *(Percent)*	**
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	2.0
Change from 1990 *(Percent)*	*27.7%*

*Less than 0.05 million metric tons carbon equivalent.
**Less than 0.05 percent.

Sulfur hexafluoride (SF_6) is used as an insulator for circuit breakers, switch gear, and other electrical equipment. In addition, its extremely low atmospheric concentration makes it a useful atmospheric tracer gas for a variety of experimental purposes. It is also a

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[48] U.S. Department of Energy, *The Climate Change Action Plan: Technical Supplement*, DOE/PO-0011 (Washington, DC, March 1994), p. 67.

[49] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), p. 64, web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[50] "PFCs Can Be Recycled with New Technology," American Institute of Chemical Engineers, Press Release (March 12, 1997).

[51] U.S. Environmental Protection Agency, Office of Air and Radiation, Atmospheric Pollution Prevention Division, personal communication, August 29, 1996.

[52] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), p. 67, web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[53] On the other hand, 3M has begun to market C_3F_8 to the semiconductor industry as a substitute for CF_4 and C_2F_6.

[54] "Environmental Protection Drives Emissions Reduction Effort," *Electronic Design* (December 1, 1997).

[55] "EPA Launches PFC Reduction Program," *Chemical Week* (July 31, 1996). Without emissions control efforts, PFC emissions would be expected to rise as the use of PFCs in the semiconductor industry increases.

[56] D. Schiff and M. Sciannamea, "Greenlook," *Electronic Design* (December 15, 1997).

fugitive emission from certain semiconductor manufacturing processes, and it is used as a cover gas during magnesium production and processing, to prevent the violent oxidation of molten magnesium in the presence of air.

Sulfur hexafluoride has a high GWP of 23,900, but it is not produced or used in large quantities. In 1989, global production and emissions were estimated at 5,000 metric tons.[57] The EPA estimates 1996 emissions of sulfur hexafluoride at 1,430 metric tons, equivalent to emissions of more than 9 million metric tons of carbon. The EPA's estimates indicate a slight decrease in emissions between 1995 and 1996, from 1,460 metric tons to 1,430 metric tons.[58]

Ozone-Depleting Substances

The impact of ozone-depleting substances on global climate is ambiguous, and they are not included among the greenhouse gases to be controlled under the Kyoto Protocol. Emissions of CFCs, HCFCs, halons, and other chlorine-containing gases are therefore considered separately in this report.

Chlorofluorocarbons (CFCs)

CFCs are derivatives of hydrocarbons. Hydrocarbons are composed of hydrogen and carbon atoms. In CFCs, the hydrogen atoms are replaced with chlorine and fluorine atoms, yielding an array of usually nontoxic, nonflammable gases useful in a wide variety of applications. CFCs have no natural source, and their high molecular stability allows them to migrate to the stratosphere, where they destroy ozone. Although molecule for molecule they absorb thousands of times more infrared radiation than does carbon dioxide, their net warming effect is reduced because of their effect on ozone. Ozone (O_3), beneficial in the stratosphere for its ability to absorb harmful ultraviolet radiation, is also a potent greenhouse gas. Thus, while the direct warming potential of CFCs is far greater than that of carbon dioxide, their indirect effect on ozone reduces their net radiative forcing effects by half (see discussion in Chapter 1).

The Copenhagen Amendments of the Montreal Protocol requires phasing out CFCs by 1996.[59] The United States is implementing these provisions through the Clean Air Act Amendments of 1990 and subsequent EPA regulations, which specify allowable production quotas and taxes on inventories and stocks. All production ceased in January 1996, with the exception of small amounts used in metered dose inhalers for asthma patients, for which no substitutes are available. Emissions of CFCs contained in mobile air conditioners, chillers, and other equipment built prior to the regulations will continue at least into the next decade.

CFC-11 is used principally as a blowing agent for foams and packaging materials and as a refrigerant in large commercial chillers. Sales have been declining steadily since 1989, with production following roughly the same trend, except for a spike in 1992.[60] In 1994, production and sales declined by nearly 80 percent, to only 7,000 metric tons,[61] implying that CFC-11 has been phased out of the blowing agent market completely, with residual CFC-11 probably used only to recharge existing chillers.

CFC-12 is often known by its trade name, "freon-12." Exceedingly versatile, its end uses include air conditioning (both automotive and commercial); refrigeration (refrigerators and freezers of varying scales); and as a blowing agent for foams, insulations, and packaging. Pursuant to the Montreal Protocol, production and sales dropped dramatically in 1990 and 1991, falling below estimates of end-use applications and emissions. In recent years, end use has gradually declined with the ongoing phaseout of CFCs.[62]

AFEAS data suggest that use of CFC-12 as a blowing agent dropped by more than 90 percent between 1988 and 1996.[63] The use of CFC-12 in refrigeration, however, declined more slowly until 1994. During 1994, automobile, refrigerator, and commercial chiller manufacturers essentially ceased using CFC-12 in their

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[57] M.K.W. Ko, N.D. Sze, W.C. Wang, G. Shia, A. Goldman, F.J. Murcray, D.G. Murcray, and C.P. Rinsland, "Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming," *Journal of Geophysical Research*, Vol. 98 (1993), p. 10,500.

[58] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), pp. 68-69, web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[59] The current (amended) text of the Montreal Protocol can be found at web site www.unep.org/unep/secretar/ozone/treaties.htm.

[60] U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1993* (Washington, DC, November 1994), p. 3-21.

[61] U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1994* (Washington, DC, March 1995), p. 3-21.

[62] U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1993* (Washington, DC, November 1994), p. 3-21.

[63] Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1996* (Washington, DC, January 1998), p. 10.

products. At present, emissions are being sustained by the existing stock of CFC-using equipment.

Other CFCs include CFC-113, CFC-114, and CFC-115. CFC-113 and CFC-114 are used principally as solvents. EPA-estimated emissions of both of these CFCs have been declining rapidly since 1989, although small CFC-114 emissions from metered dose inhalers are likely to continue for a few more years. The EPA granted the International Pharmaceutical Aerosol Consortium 338 metric tons of CFC-114 essential use allowances for 1998.[64] CFC-115 is used primarily as a blending agent for some specialty refrigerants. CFC-115 emissions have also declined during the 1990s, although not as rapidly as CFC-113 and CFC-114 emissions.

Hydrochlorofluorocarbons (HCFCs)

HCFCs are essentially CFCs that include one or more hydrogen atoms. The presence of hydrogen makes the resulting compounds less stable, and as a result they are more susceptible to photodecomposition, have much shorter atmospheric lifetimes than CFCs, and are less likely to migrate to the stratosphere where they would destroy ozone. They are therefore popular interim substitutes for CFCs. The Copenhagen Amendments placed HCFCs under control, with HCFC-22 slated for elimination by 2020 and all others by 2030.

HCFC-22 is the most commonly used refrigerant for home air conditioning systems. It is the most widely available and least expensive potential substitute for CFCs in a variety of applications; however, the available evidence suggests that HCFC-22 gained most of its market share at the expense of CFCs in the late 1980s. Nonetheless, use of HCFC-22 for long- and medium-lifetime applications has created a “banked” inventory of the compound that is now being emitted at a rate of 70,000 to 80,000 metric tons per year.

A number of other HCFCs are gaining importance as CFCs are phased out. HCFC-141b is used primarily as a solvent and as a blowing agent for closed-cell foams, and HCFC-142b is used mainly for long-lifetime applications—particularly as a blowing agent for closed-cell foams. HCFC-123 is a replacement for CFC-11 in refrigeration applications, and HCFC-124 is a potential replacement for CFC-12 in sterilizers. EPA-estimated emissions of all these HCFCs have risen rapidly, from negligible levels in the early 1990s.

Bromofluorocarbons (Halons)

Bromofluorocarbons are similar to CFCs except that they contain at least one bromine atom. They are inert, nontoxic, and evaporate without leaving any residue, making them popular for use as fire suppressants for high-value equipment, such as computer centers and aircraft. The trade name “halon” is applied to several of these chemicals, which are used as fire suppressants. Halons are particularly destructive to stratospheric ozone; consequently, production ceased in 1996 pursuant to the Montreal Protocol. However, attempts to smuggle halon-1301 into the United States have been reported.[65] Emissions of halons are low, although the exact figure is uncertain.

Other Chemicals

Several other chemicals combine high GWPs and significant emissions levels to produce potential effects on global climate: carbon tetrachloride, methyl chloroform, chloroform, and methylene chloride. Several of these chemicals are regulated under the Clean Air Act Amendments of 1990.

Most carbon tetrachloride is used as a feedstock in the production of CFC-11 and CFC-12. Carbon tetrachloride is regulated by the Clean Air Act Amendments as a known carcinogen and under the Montreal Protocol as an ozone-depleting chemical. Production ceased in January 1996. Emissions declined rapidly in the 1990s and, according to the EPA, reached negligible levels in 1996.

Like carbon tetrachloride, methyl chloroform is regulated under the Clean Air Act Amendments as an ozone-depleting chemical covered by the Montreal Protocol. Used primarily as a solvent, it was required to be phased out by 1996. Emissions have declined rapidly, from about 160,000 metric tons in 1990 to 4,000 metric tons in 1996. For 1998, the EPA has granted the National Aeronautics and Space Administration and the Air Force a total of 60 metric tons of essential use allowances for the use of methyl chloroform in cleaning, bonding, and surface activation applications on the space shuttle and the Titan rocket.[66]

Chloroform is used primarily as a feedstock for HCFC-22, with secondary use as a solvent. It is a weak greenhouse gas with a GWP of 5. Total emissions should be low, because most chloroform is incorporated

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[64] U.S. Environmental Protection Agency, *Ozone Depleter Compliance Guide* (March 1998).
[65] “Justice Department Adds to CFC Indictments,” *Ozone Depletion Today* (Alexandria, VA, February 27, 1998).
[66] U.S Environmental Protection Agency, *Ozone Depleter Compliance Guide* (March 1998).

into HCFC-22 during its production. As a carcinogen, chloroform is reported to the EPA's Toxics Release Inventory (TRI). The TRI indicates that emissions have been decreasing and were only 4,400 metric tons in 1996.[67]

Like chloroform, methylene chloride is a weak greenhouse gas (GWP of 9). Its short atmospheric lifetime of less than 1 year probably prevents it from reaching the stratosphere where it would be damaging to ozone. As a result, its indirect cooling effects are likely to be small. A potential carcinogen, methylene chloride emissions are regulated and included in the TRI, with 1996 emissions of 24,600 metric tons, down significantly from 46,000 metric tons in 1990.[68]

Criteria Pollutants That Affect Climate

U.S. Emissions of Criteria Pollutants, 1990-1996

	Million Metric Tons of Gas		*Percent Change*	
Source	**1990**	**1996**	**1990-1996**	**1995-1996**
Carbon Monoxide	87.4	80.4	*-8.0%*	*-1.0%*
Nitrogen Oxides	21.6	21.3	*-1.4%*	*-2.0%*
Nonmethane Volatile Organic Compounds	18.9	17.2	*-9.0%*	*-7.3%*

Overview

Certain criteria pollutants also affect climate: carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic compounds (NMVOCs).[69] The Clean Air Act of 1970 required that air quality standards be established for pollutants with adverse effects on public health or welfare. They are termed "criteria pollutants" because the EPA based each National Ambient Air Quality Standard (NAAQS) on health-based criteria from scientific studies. Although these gases are not considered to be greenhouse gases themselves, estimates of their emissions are presented here because of their indirect effects on atmospheric concentrations of greenhouse gases, including carbon dioxide, methane, and ozone.

Ozone is produced largely from atmospheric chemical reactions involving these criteria pollutants. Ozone is highly reactive with other atmospheric gases, and its concentration is influenced by meteorological conditions. As a result, it remains in the troposphere for only hours or days. Hence, concentrations of tropospheric ozone tend to be centered around cities where high levels of criteria pollutants are found. Ozone concentrations are measured at individual urban sites throughout the United States. The EPA reported that the composite average ozone concentration for its 600 U.S. testing sites has declined by 15 percent since 1987.[70]

The EPA Office of Air Quality Planning and Standards has compiled emissions data for the various criteria pollutants in the document *National Air Pollutant Emission Trends, 1900-1996.*[71] The emissions estimates in this report are taken from that document. The EPA continues to modify emissions data with improved estimation methods and updated information.

Since the passage of the Clean Air Act of 1970 and subsequent amendments, implementation of pollution control measures and replacement of older, less fuel-efficient vehicles have restrained potential growth in criteria pollutant emissions that otherwise would have been expected from growth in the economy, increased driving, and expansion of industrial output. Current emissions of both carbon monoxide and NMVOCs are significantly below peak levels seen in the early 1970s, despite year-to-year fluctuations. Although emissions of nitrogen oxides are now higher than in 1970, the level of emissions has been relatively stable in the 1990s.

Carbon Monoxide

Most emissions of carbon monoxide result from incomplete oxidation during combustion of fuels used for transportation. Transportation emissions, primarily

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[67] U.S. Environmental Protection Agency, *1996 Toxics Release Inventory: Public Data Release—Ten Years of Right-to-Know* (Washington, DC, May 1998), p. 68, web site www.epa.gov/opptintr/tri/pdr98/drhome.htm.

[68] U.S. Environmental Protection Agency, *1996 Toxics Release Inventory: Public Data Release—Ten Years of Right-to-Know* (Washington, DC, May 1998), p. 72, web site www.epa.gov/opptintr/tri/pdr98/drhome.htm.

[69] All estimates and projections presented in this chapter are taken directly from U.S. Environmental Protection Agency, *National Air Pollutant Emission Trends, 1900-1996,* EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), web site www.epa.gov/oar/emtrnd.

[70] U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Quality and Emissions Trends Report, 1996,* EPA-454-R-97-013 (Research Triangle Park, NC, January 1998), p. 80, web site www.epa.gov/oar/aqtrnd96.

[71] U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1996,* EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), web site www.epa.gov/oar/emtrnd.

from highway vehicles, accounted for about 79 percent of 1996 emissions. Total emissions in 1996 amounted to about 80.4 million metric tons, an amount considerably below the 128.8 million metric tons seen in 1970 (Table 33). Between 1990 and 1996, carbon monoxide emissions decreased by 8.0 percent, due largely to decreases in emissions of approximately 4 million metric tons each from highway vehicles (down by 8.5 percent) and forest fires (down by 75.2 percent). Otherwise, 1996 emissions were generally the same as or slightly above 1990 levels. One exception was emissions from "other off-highway vehicles," which were not as well controlled as other sources. Emissions from this source during 1996 were 0.8 million metric tons (5.7 percent) higher than in 1990. Carbon monoxide emissions are expected to decrease through the year 2000 as a result of more stringent tailpipe standards and other factors.

Nitrogen Oxides

Nitrogen oxide emissions are related to air-fuel mixes and combustion temperatures during the burning of fuels. Emissions are reduced by the use of pollution control equipment, such as catalytic converters. Since 1990, total U.S. emissions of nitrogen oxides have hovered around 22 million metric tons per year (Table 34). Although this does not represent a decline (as seen with the other criteria pollutants), it is much lower than the rate of growth in fuel consumption (such as consumption of gasoline by motorists and coal by electric utilities). Emissions are split between transportation and stationary sources. Total emissions of nitrogen oxide during 1996 (21.3 million metric tons) were about 1.4 percent lower than their 1990 level of 21.6 million metric tons. Emissions are expected to decline with implementation of various additional emissions control measures.

Nonmethane Volatile Organic Compounds

NMVOCs are a principal component in the chemical and physical atmospheric reactions that form ozone and other photochemical oxidants. Nearly half (47.6 percent) of the 17.2 million metric tons of NMVOC emissions during 1996 came from industrial processes (Table 35), of which solvent use was the largest source. Most (80.0 percent) of the remaining 9.0 million metric tons of emissions were from combustion of transportation fuels. Emissions of NMVOCs declined by some 11.7 million metric tons (38.1 percent) from 1970 to 1996, while fuel consumption in the transportation sector increased and activity in the industrial sector expanded.[72] This improvement was accomplished by some reformulation of petroleum products, implementation of pollution abatement measures, and changes in industrial processes. Emissions from solvent utilization declined as a result of the substitution of water-based emulsified asphalt for asphalt liquefied with petroleum distillates.

Emissions of NMVOCs were 17.2 million metric tons in 1996, down 7.3 percent from their level in 1995, and down by 9.0 percent (1.7 million metric tons) from 1990 levels. During 1996, energy-related activities (transportation and stationary source fuel combustion) accounted for approximately 43.7 percent (0.7 million metric tons) of the total decrease of 1.7 million metric tons in emissions of NMVOCs, compared with 1990 levels. Solid waste disposal sources accounted for 29.6 percent (0.5 million metric tons) of the decrease in emissions from 1990.

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[72] U.S. Environmental Protection Agency, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), web site www.epa.gov/oar/emtrnd.

Table 31. Estimated U.S. Emissions of Halocarbons and Miscellaneous Greenhouse Gases, 1990-1997
(Thousand Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	P1997
Chlorofluorocarbons (CFCs)								
CFC-11	54	48	45	45	37	36	27	22
CFC-12	113	104	81	79	58	52	36	24
CFC-113	26	21	17	17	9	9	*	*
Other CFCs	9	8	7	7	5	5	4	3
Halons	3	3	3	3	2	3	3	2
Hydrochlorofluorocarbons (HCFCs)								
HCFC-22	80	80	80	71	71	74	77	81
HCFC-141b	0	0	0	2	7	12	14	18
HCFC-142b	0	0	4	9	15	21	28	34
Other HCFCs	0	0	1	3	6	7	7	8
Hydrofluorocarbons (HFCs)								
HFC-23	3	3	3	3	3	2	3	3
HFC-134a	1	1	1	3	5	10	14	18
HFC-152a	3	3	*	1	1	1	1	1
Other HFCs	0	0	*	1	4	8	10	12
Perfluorocarbons (PFCs)	3	3	3	2	2	3	3	3
Other Chemicals								
Carbon Tetrachloride	32	31	22	19	16	5	*	*
Methyl Chloroform	158	155	108	93	77	46	4	*
Sulfur Hexafluoride	1	1	1	1	1	1	1	1

*Less than 500 metric tons.

P = preliminary data.

Sources: **1990-1996:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html. **1997:** Estimated from methods described in Appendix A.

Table 32. Estimated GWP-Weighted U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1997
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	P1997
Hydrofluorocarbons (HFCs)								
HFC-23	9.51	8.39	9.51	8.71	8.62	7.43	8.58	8.62
HFC-134a	0.20	0.20	0.22	1.02	1.92	3.39	4.83	6.28
HFC-152a	0.10	0.10	0.01	0.03	0.03	0.04	0.04	0.05
HFC-125	0.00	0.00	0.18	0.37	1.24	2.15	2.42	3.01
HFC-227	0.00	0.00	0.00	0.00	0.70	1.49	1.63	2.09
HFC-143a	0.00	0.00	0.00	0.01	0.04	0.09	0.24	0.34
HFC-4310	0.00	0.00	0.00	0.00	0.00	0.22	0.37	0.44
Total	**9.81**	**8.69**	**9.93**	**10.14**	**12.56**	**14.82**	**18.10**	**20.82**
Perfluorocarbons (PFCs)								
CF_4	4.57	4.65	4.56	4.17	3.72	3.81	4.04	4.07
C_2F_6	0.61	0.62	0.61	0.56	0.50	0.51	0.54	0.54
C_4F_{10}	0.00	0.00	0.00	0.00	0.00	0.05	0.15	0.25
PFCs/PFPEs	0.00	0.00	0.00	0.00	0.08	2.48	2.48	2.51
Total	**5.18**	**5.27**	**5.17**	**4.73**	**4.30**	**6.85**	**7.21**	**7.37**
Sulfur Hexafluoride	7.30	7.76	8.15	8.60	9.06	9.52	9.32	9.32
Total Emissions	**22.29**	**21.72**	**23.25**	**23.47**	**25.91**	**31.19**	**34.64**	**37.51**

P = preliminary data.

Sources: **1990-1996:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html. **1997:** Estimated from methods described in Appendix A. Global warming potentials used to convert emissions to carbon-equivalent basis from Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 119 and 121.

Table 33. U.S. Carbon Monoxide Emissions, 1990-1997
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Transportation								
Highway Vehicles	52.48	56.31	54.30	54.61	56.09	49.08	48.03	NA
Aircraft	0.82	0.81	0.82	0.82	0.83	0.85	0.86	NA
Railroads	0.11	0.11	0.11	0.11	0.10	0.10	0.10	NA
Vessels	0.08	0.08	0.08	0.07	0.07	0.07	0.07	NA
Other Off-Highway	13.62	13.56	13.85	14.05	14.30	14.25	14.39	NA
Total	**67.10**	**70.86**	**69.16**	**69.67**	**71.40**	**64.36**	**63.45**	**NA**
Stationary Source Fuel Combustion								
Electric Utilities	0.33	0.32	0.32	0.33	0.34	0.34	0.34	NA
Industrial	0.80	0.83	0.87	0.95	0.94	0.96	0.97	NA
Commercial-Institutional	0.07	0.07	0.08	0.08	0.08	0.08	0.08	NA
Residential	3.67	3.97	4.19	3.59	3.52	3.88	3.87	NA
Total	**4.86**	**5.18**	**5.45**	**4.94**	**4.87**	**5.25**	**5.26**	**NA**
Total Energy-Related Emissions	**71.96**	**76.05**	**74.61**	**74.61**	**76.27**	**69.61**	**68.71**	**NA**
Industrial Processes	**4.33**	**4.19**	**4.12**	**4.22**	**4.18**	**4.18**	**4.19**	**NA**
Solid Waste Disposal								
Incineration	0.34	0.36	0.37	0.45	0.42	0.39	0.40	NA
Open Burning	0.64	0.65	0.66	0.68	0.68	0.68	0.69	NA
Total	**0.98**	**1.01**	**1.03**	**1.13**	**1.11**	**1.07**	**1.09**	**NA**
Miscellaneous								
Forest Fires	5.38	3.11	1.52	1.44	3.73	1.33	1.33	NA
Other Burning	4.79	4.83	4.88	4.92	4.99	5.06	5.11	NA
Total	**10.17**	**7.94**	**6.40**	**6.36**	**8.72**	**6.39**	**6.44**	**NA**
Total All Sources	**87.44**	**89.19**	**86.16**	**86.32**	**90.29**	**81.26**	**80.43**	**NA**
Carbon Content of Carbon Monoxide	37.49	38.25	36.95	37.01	38.72	34.84	34.49	NA
Carbon Content of Energy-Related Carbon Monoxide	30.86	32.61	31.99	31.99	32.71	29.85	29.47	NA

NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), Table A-1, pp. A-2–A-6, web site www.epa.gov/oar/emtrnd.

Table 34. U.S. Nitrogen Oxide Emissions, 1990-1997
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Transportation								
Highway Vehicles	6.39	6.69	6.75	6.81	6.96	6.64	6.51	NA
Aircraft	0.14	0.14	0.14	0.14	0.15	0.15	0.15	NA
Railroads	0.84	0.84	0.86	0.86	0.86	0.90	0.90	NA
Vessels	0.21	0.22	0.21	0.20	0.20	0.21	0.21	NA
Other Off-Highway	2.97	2.90	3.01	3.13	3.28	2.99	2.99	NA
Total	**10.55**	**10.79**	**10.98**	**11.14**	**11.45**	**10.88**	**10.75**	**NA**
Stationary Source Fuel Combustion								
Electric Utilities	6.04	5.91	5.90	6.03	5.96	5.79	5.47	NA
Industrial	2.75	2.70	2.79	2.86	2.85	2.85	2.88	NA
Commercial-Institutional	0.31	0.30	0.32	0.33	0.34	0.34	0.34	NA
Residential	0.75	0.83	0.88	0.83	0.82	0.81	0.80	NA
Total	**9.85**	**9.75**	**9.89**	**10.05**	**9.97**	**9.79**	**9.49**	**NA**
Total Energy-Related Emissions	**20.41**	**20.54**	**20.86**	**21.20**	**21.41**	**20.68**	**20.24**	**NA**
Industrial Processes	**0.73**	**0.65**	**0.69**	**0.67**	**0.69**	**0.70**	**0.71**	**NA**
Solid Waste Disposal								
Incineration	0.04	0.05	0.05	0.07	0.06	0.05	0.05	NA
Open Burning	0.04	0.04	0.04	0.04	0.04	0.04	0.04	NA
Total	**0.08**	**0.09**	**0.09**	**0.11**	**0.10**	**0.09**	**0.09**	**NA**
Miscellaneous								
Forest Fires	*	*	*	*	*	*	*	NA
Other Burning	0.34	0.26	0.23	0.20	0.35	0.21	0.22	NA
Total	**0.34**	**0.26**	**0.23**	**0.20**	**0.35**	**0.21**	**0.22**	**NA**
Total All Sources	**21.55**	**21.54**	**21.87**	**22.18**	**22.55**	**21.68**	**21.26**	**NA**

*Less than 5,000 metric tons.

NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), Table A-2, pp. A-7–A-11, web site www.epa.gov/oar/emtrnd.

Table 35. U.S. Emissions of Nonmethane Volatile Organic Compounds, 1990-1997
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Transportation								
Highway Vehicles	5.73	5.90	5.51	5.54	5.81	5.17	4.99	NA
Aircraft	0.16	0.16	0.16	0.16	0.16	0.16	0.16	NA
Railroads	0.05	0.05	0.05	0.05	0.04	0.04	0.04	NA
Vessels	0.04	0.05	0.05	0.04	0.04	0.04	0.04	NA
Other Off-Highway	2.01	2.02	2.06	2.09	2.13	1.96	1.95	NA
Total	**8.00**	**8.17**	**7.82**	**7.88**	**8.18**	**7.38**	**7.19**	**NA**
Stationary Source Fuel Combustion								
Electric Utilities	0.04	0.04	0.04	0.04	0.04	0.04	0.04	NA
Industrial	0.17	0.18	0.17	0.17	0.18	0.19	0.19	NA
Commercial-Institutional	0.01	0.01	0.01	0.01	0.01	0.01	0.01	NA
Residential	0.69	0.74	0.78	0.67	0.66	0.73	0.72	NA
Total	**0.90**	**0.97**	**1.00**	**0.89**	**0.89**	**0.97**	**0.97**	**NA**
Total Energy-Related Emissions	**8.90**	**9.13**	**8.83**	**8.77**	**9.07**	**8.35**	**8.16**	**NA**
Industrial Processes	**8.18**	**8.33**	**8.50**	**8.65**	**8.79**	**8.81**	**8.21**	**NA**
Solid Waste Disposal								
Incineration	0.04	0.05	0.05	0.07	0.06	0.05	0.05	NA
Open Burning	0.18	0.18	0.18	0.19	0.19	0.19	0.19	NA
Other	0.67	0.68	0.69	0.69	0.70	0.73	0.15	NA
Total	**0.89**	**0.91**	**0.92**	**0.95**	**0.95**	**0.97**	**0.39**	**NA**
Miscellaneous								
Forest Fires	0.68	0.40	0.15	0.19	0.34	0.16	0.16	NA
Other Burning	0.27	0.29	0.29	0.29	0.30	0.31	0.31	NA
Total	**0.95**	**0.69**	**0.44**	**0.49**	**0.65**	**0.46**	**0.47**	**NA**
Total All Sources	**18.92**	**19.05**	**18.68**	**18.85**	**19.46**	**18.59**	**17.23**	**NA**

NA = not available.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), Table A-3, pp. A-12–A-18, web site www.epa.gov/oar/emtrnd.

6. Land Use Issues

Overview

Land use patterns play an important role in greenhouse gas emissions and sequestration in the United States. Land use types that affect greenhouse gas emissions and sequestration include forest land, grassland, pasture, rangeland, cropland, wetlands, and urban land.[73] The effects of land use on national emissions estimates are complicated by two issues:

- Distinguishing between anthropogenic (human-made) and biogenic (natural) emissions and sequestration from land use and forestry.
- Reliably estimating national-level anthropogenic emissions and sequestration from land use and forestry.

This chapter focuses primarily on the second issue: describing the candidate sources of emissions and sequestration in a U.S. context and analyzing the ways in which changing definitions of what should be included or excluded can alter the estimate of net emissions and sequestration. Specifically:

- The Kyoto Protocol specifies that national greenhouse gas emissions and sequestration will be estimated in accord with guidelines and methods promulgated by the Intergovernmental Panel on Climate Change (IPCC). However, there are discrepancies between forestry accounting methods implied by the Kyoto Protocol and the IPCC guidelines, which make it difficult to determine the correct national aggregate greenhouse gas emissions and reductions attributable to land use.
- Changes in forest and other land uses may significantly affect the stringency of the policy interventions that would required to comply with the Kyoto Protocol. Annual net sequestration by forest land and other land in the United States may be as high as 227 million metric tons per year or as low as a few million metric tons, depending on which categories of emissions and sequestration are excluded or included.
- National estimates for annual greenhouse gas flux on grassland, pasture, rangeland, and cropland are required under the IPCC guidelines but absent from the Kyoto Protocol, and U.S. estimates are currently unavailable.

Substantial quantities of greenhouse gases are removed from the atmosphere by natural processes in terrestrial systems each year. A similarly substantial, although smaller quantity is released back into the atmosphere by the reverse of these natural processes each year. In the United States, annual aggregate sequestration of greenhouse gases attributable to all land use types is, and is likely to be for decades, greater than emissions.

Carbon dioxide, nitrous oxide, and methane are both emitted and absorbed by soils and vegetation in the United States. Changes in land use can produce large changes in the balance between emissions and absorption. Carbon dioxide accounts for most of the emissions and absorption, primarily by forests, but with lesser amounts absorbed or emitted by grasslands, pasture, and rangeland. Methane and nitrous oxide are also emitted and absorbed in smaller quantities by bacterial action in soils and wetlands. As discussed in Chapter 4, anthropogenic soil fertilization with nitrogen in the form of fertilizer or manure enhances natural bacterial action that causes emissions of nitrous oxide.

The Role of Land Use in Greenhouse Gas Emissions and Reductions

Sources and sinks of greenhouse gases related to land use are difficult both to quantify and to categorize. Quantification ultimately relies on direct measurements and extrapolations therefrom. Because the land area of the United States equals 2.26 billion acres (Table 36), direct measurements of even a sample of representative land use types are expensive, complex, and time-consuming.

Categorization of land use types is difficult, because land frequently shifts from one category to another, blurring definitions. For example, grassland recently converted from cropland is categorized as grassland,

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[73] In this document, the meaning of the term “land use” includes both uses of land and types of land cover. In general, land use refers to the purpose of human activity on the land; land cover refers to the vegetation or other kind of material that covers the land surface. In this document, both definitions are incorporated under the single term “land use.”

Table 36. Major Uses of Land in the United States
(Million Acres)

Land Use	1978	1982	1987	1992
Cropland	471	469	464	460
Used for Crops	369	383	331	338
Idle Cropland	26	21	68	56
Pasture	76	65	65	67
Grassland Pasture and Range	587	597	591	591
Forest-Use Land	703	655	648	648
Grazed Land	172	158	155	145
Other Use	531	497	493	503
Special Use Areas	158	270	279	281
Miscellaneous Other Land	345	274	283	283
Total Land Area	**2,264**	**2,265**	**2,265**	**2,263**

Sources: A. Daugherty, *Major Uses of Land in the United States: 1987*, Economic Research Service Report 643 (Washington, DC: U.S. Department of Agriculture, January 1991), p. 4; and A. Daugherty, *Major Uses of Land in the United States: 1992*, Agricultural Economic Report Number 723 (Washington, DC, September 1995), p. 4.

even though its soil carbon content, the most important carbon sink in grasslands, more closely matches that of cropland, which typically contains far less soil carbon. Similarly, a dense forest stand may be reclassified as urban land as the result of surrounding urban development, even if the forest, and its carbon dynamics, are unchanged. Forest may also be reclassified as park land, even if no forest is removed in the transition. The result may be the appearance of a decrease in forest area in national inventories when, in fact, there has been no change.

Calculating Greenhouse Gas Emissions and Reductions Under the Kyoto Protocol

The IPCC Guidelines

For purposes of estimating greenhouse gas emissions and reductions attributable to land use, the IPCC has released guidelines on greenhouse gas accounting for land use change and forestry (the “IPCC guidelines”).[74] Under the Kyoto Protocol, participating nations must follow the IPCC guidelines when calculating greenhouse gas emissions and reductions. The guidelines consist of specific instructions for estimating greenhouse gas emissions and reductions from all potential anthropogenic and natural sources and sinks, and they call for national estimates of 1990 aggregate carbon dioxide equivalent emissions of greenhouse gases, which will serve as a baseline against which national emissions during the period 2008-2012 will be compared.

One of the ways in which the United States and other countries may reach their emissions reduction goals, if they ratify the Kyoto Protocol, is by accounting for and, potentially, enhancing net sequestration of greenhouse gases from the atmosphere by natural processes in forests, grasslands, pasture, and rangelands. The IPCC guideline on “Land Use Change and Forestry” calls for greenhouse gas accounting under four categories:

- Changes in forest and other woody biomass stocks
- Forest and grassland conversion
- Abandonment of croplands, pastures, plantation forests, or other managed lands
- Changes in soil carbon.

The categories are intended to capture all greenhouse gas emissions and sequestration caused by land uses and the processes that occur on them. The greenhouse gas effects in each category can be estimated for the United States; however, the data cannot support estimates of all dimensions of possible change in carbon flux.

It is uncertain whether all four of the IPCC categories for “Land Use Change and Forestry” will be allowable under accounting procedures for the Kyoto Protocol. The Kyoto Protocol specifically calls for use of the IPCC

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[74] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 5.1-5.75, web site www.iea.org/ipcc/invs6.htm.

guidelines;[75] the latest IPCC methods include all four categories listed above. However, the Protocol specifically states that allowable land use change and forestry activities should be limited to ". . . afforestation, reforestation, and deforestation,"[76] potentially excluding grassland conversion, abandonment of managed lands, and certain changes in soil carbon. No decision has been made by the parties to the Kyoto Protocol as to which IPCC categories or parts of categories will be allowed and which will be excluded.

Table 37 presents some relevant components of forestry and land use change and indicates whether they are included in, or excluded from, the Kyoto Protocol and IPCC guidelines, respectively. A total of 11 components are shown, organized into the four "Land Use Change and Forestry" categories of the IPCC guidelines. For the first six components, labeled B through G to correspond with the same components in Table 38, carbon flux estimates and projections have been produced by the U.S. Forest Service. The last five components are not included in Table 38 (and hence are unlabeled), because estimates of the U.S. carbon flux for these components are not currently available.

The purpose of Table 37 to highlight some of the key areas where the IPCC guidelines differ from the Kyoto Protocol in terms of the type of land use change and forestry data included in each. The IPCC guidelines call for a greater range of data types than does the Kyoto Protocol. Because the IPCC guidelines are intended to serve as the reporting mechanism under the Kyoto Protocol, such important differences would have to be clarified before reporting could commence in the year 2008.

Baseline and Commitment Period

The Kyoto Protocol calls for inclusion of land use and forestry-related greenhouse gas emissions and removals in baseline 1990 emissions only from "Those parties . . . for whom land use change and forestry constituted a net source of greenhouse gas emissions in 1990."[77] In the United States, land use and forestry-related greenhouse gas emissions and sequestration constituted a net *sink* in 1990. Therefore, the United States could include net sequestration from forests in 2008-2012 as an offset from other greenhouse gas emissions during the commitment period, but would not have to make a similar offset against baseline emissions in 1990. In other words, any sequestration applicable under the Kyoto Protocol would reduce the stringency of the U.S. target for other greenhouse gases.

Further, to verify whether the United States is meeting its greenhouse gas reduction goal, it would be necessary to report on aggregate emissions and removals of greenhouse gases during each year of the commitment period 2008-2012. Participants are required to ". . . have in place, no later than one year prior to the start of the first commitment period, a national system for the estimation of anthropogenic emissions by sources and removals by sinks of all greenhouse gases."[78]

Data necessary for such reporting may not be available in the year 2007 or for specific years in the 2008-2012 commitment period. The most important statistics on forest and other land necessary for estimates of greenhouse gas fluxes in the United States are updated by the USDA Forest Service on average only once every 5 years, and full reports containing the data are released only once every 10 years.[79] However, one of the provisions under consideration in Congress in the current version of the Farm Bill is a new USDA Forest Service mandate to collect and report national forest statistics on an annual basis.[80] If this measure is ultimately included in the Farm Bill, it would satisfy the Kyoto Protocol requirement for annual reporting during the 5-year period 2008-2012.

Changes in Forest and Other Woody Biomass Stocks

There is no established method for applying the IPCC guidelines to available data on forest land and the fate of wood and paper product pools for purposes of the category "Changes in Forest and Other Woody Biomass Stocks." The figure in any given year would depend on a variety of factors that influence biomass-related carbon sequestration and emissions. The following

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[75] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change,* FCCC/CP/1997/L.7/Add.1 (1997), Article 5, Paragraph 2, web site www.unfccc.de/index.html.

[76] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change,* FCCC/CP/1997/L.7/Add.1 (1997), Article 3, Paragraph 3, web site www.unfccc.de/index.html.

[77] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change,* FCCC/CP/1997/L.7/Add.1 (1997), Article 3, Paragraph 7, web site www.unfccc.de/index.html.

[78] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change,* FCCC/CP/1997/L.7/Add.1 (1997), Article 5, Paragraph 1, web site www.unfccc.de/index.html.

[79] D.S Powell, J.L. Faulkner, D.R. Darr, Z. Zhu, and D.W. MacCleery, *Forest Resources of the United States, 1992,* USDA Forest Service General Technical Report RM-234 (Washington, DC, September 1993), p. 122.

[80] L.S. Heath, USDA Forest Service Pacific Northwest Research Station, personal communication, June 1998.

Table 37. Comparison of Components of Forestry and Land Use Change Included in the Kyoto Protocol and IPCC Guidelines

IPCC Category	Label in Table 38	Category	Included in Kyoto Protocol?	Included in IPCC Guidelines?
Changes in Forest and Other Woody Biomass Stocks	B	Carbon flux, timberland only	Y	Y
	C	Carbon flux, reserved and other forest land	N(?)	Y
	D	Carbon stored in wood products	N(?)	Y
	E	Carbon stored in landfills	N(?)	Y
	F	Carbon emitted from wood burned for energy	N(?)	Y
	G	Carbon emitted from decay and non-energy burning	N(?)	Y
Forest and Grassland Conversion	None	Carbon emitted from forest conversion to agricultural uses	Y	Y
		Carbon emitted from grassland conversion to agricultural uses	N	Y
Abandonment of Managed Lands	None	Carbon sequestered on abandoned formerly managed lands that revert to forest	Y	Y
	None	Carbon sequestered on abandoned formerly managed lands that revert to grassland	N	Y
Changes in Soil Carbon	None	Changes in soil carbon	?	Y

Source: Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 5.1-5.50, web site www.iea.org/ipcc/invs6.htm.

Table 38. Components of U.S. Net Carbon Flux, Storage, and Emissions by Source, 1997 and 2010

(Million Metric Tons of Carbon)

Label	Category	1997	2010
A	Net Carbon Flux, U.S. Forest Land (B + C)	197	192
B	Carbon Flux, Timberland Only	161	177
	Of which, live flux (trees and understory)	*69*	*61*
	Of which, dead flux (soil carbon and litter)	*92*	*117*
C	Carbon Flux, Reserved and Other Forest Land	36	15
D	Carbon Stored in Wood Products	13	14
E	Carbon Stored in Landfills	17	21
F	Carbon Emitted, Wood Burned for Energy	-55	-65
G	Carbon Emitted, Decay and Non-energy Burning	-53	-60

Source: R.A. Birdsey and L.S. Heath, “Carbon Changes in U.S. Forests,” in L.A. Joyce (ed.), *Productivity of America’s Forests and Climate Change*, General Technical Report RM-GTR-271 (Fort Collins, CO: USDA Forest Service, 1995)., pp. 64-65, 67.

seven factors, labeled A through G, may be included or excluded, depending on the final method ultimately adopted by the United States and other signatories to the Kyoto Protocol (see also Table 38):

A = Carbon flux on all U.S. forest land (sum of B + C)

B = Carbon flux on timberland only

C = Carbon flux on non-timberland (reserved and other forest land not managed for wood products)

D = Carbon stored in wood products

E = Carbon stored in landfills

F = Carbon released due to wood burning for energy

G = Carbon emitted due to wood decay and non-energy wood burning.

Estimates for all these carbon sources and sinks (Table 38) were obtained from a report by USDA Forest Service researchers Richard Birdsey and Linda Heath.[81] A linear interpolation between Birdsey and Heath's 1992 and 2000 net flux estimates was used to derive the estimates for 1997. Projections for the fluxes in 2010 are taken directly from their report.

Depending on the final accounting methods adopted for the category "Changes in Forest and Other Woody Biomass Stocks," aggregate net carbon flux due to land use change and forestry could vary considerably. At the high end, aggregate net carbon flux could be calculated as net flux on all U.S. forest land (factor A), plus carbon stored in wood products and landfills (factors D and E), for a total of 227 million metric tons sequestered in both 1997 and 2010. At the low end, if flux for land uses other than timberland (factor C) were excluded, as well as carbon storage in wood products and landfills (factors D and E), and if emissions from wood burning and decay were included (factors F and G), aggregate net carbon flux would equal 53 million metric tons sequestered in 1997 and 52 million metric tons sequestered in 2010.

From the standpoint of net carbon emissions and removals from the atmosphere in any given year, it could be argued that carbon emitted from wood burning for energy (factor F) and from wood decay and non-energy burning (factor G) should be subtracted from the net flux from timberland (factor B) to arrive at the estimate for "Changes in Forest and Other Woody Biomass Stocks." This would be in keeping with the emphasis in the IPCC guidelines on estimating all emissions and removals in the inventory year, regardless of whether such emissions and removals were influenced by processes that occurred before the inventory year.

The justification is as follows: flux on timberland could be included because the IPCC guidelines call for estimates of fluxes on all land managed for wood products; carbon emissions from wood burned for energy and from decaying wood and non-energy burning could be included, because they represent releases of carbon to the atmosphere in the inventory year; fluxes on reserved and other forest land could be excluded, because the lands are not managed for wood products; and finally, carbon storage in wood products and landfills could be excluded, because such storage represents merely a transfer of previously sequestered carbon from forests to product and waste pools, rather than a sequestration of carbon from the atmosphere during the inventory year. Adherence to this accounting method would result in the low-end net carbon sequestration rate estimate of 53 million metric tons sequestered in 1997 and a projected 52 million metric tons sequestered in 2010.

Previous estimates of net carbon flux on U.S. forest land in this report have represented factor A only (net carbon flux on all U.S. forest land). That estimation method may or may not match the method that ultimately would be adopted by the United States for purposes of reporting aggregate net carbon-dioxide-equivalent emissions of greenhouse gases resulting from land use change and forestry under the Kyoto Protocol.

The IPCC's category "Changes in Forest and Other Woody Biomass Stocks" includes all emissions and sequestration of greenhouse gases from forests managed for wood products and from wood products and waste pools. Forests not managed for wood products are not included, because they are not considered to be either an anthropogenic source or sink of greenhouse gases.[82]

If the probable methodology described above is adopted (factor B minus factors F and G), the substantial quantity of carbon sequestered on reserved and other forest land (e.g., land in parks, wilderness, and conservation areas) would be excluded from the accounting under the category "Changes in Forest and Other Woody Biomass Stocks." However, it might be possible to include those lands under another IPCC

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[81] R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in L.A. Joyce (ed.), *Productivity of America's Forests and Climate Change*, General Technical Report RM-GTR-271 (Fort Collins, CO: USDA Forest Service, 1995).

[82] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 5.11, web site www.iea.org/ipcc/invs6.htm.

category, "Abandonment of Managed Lands," discussed below.

More than 50 percent of the carbon in forest ecosystems is found in the soil.[83] However, the IPCC guideline category "Change in Soil Content" includes only soil carbon on non-forest land. The role of soil carbon in forests has yet to be determined under the Kyoto Protocol.

Forest and Grassland Conversion

The IPCC's category "Forest and Grassland Conversion" includes conversion of forests and grasslands to other land uses, such as highways, urban development, and agricultural land. Although included under the IPCC's "Land Use Change and Forestry" section, there is uncertainty as to whether this category will be allowable under national greenhouse gas accounting for purposes of the Kyoto Protocol, because grassland conversion is not mentioned in the Protocol.

Of the three IPCC categories under the "Land Use Change and Forestry" section, this category is the most complex and difficult to quantify. The greenhouse gas effect of converting a forest or grassland to another land use depends on many factors, including the history of the land area, the type of land use after conversion, temperature and humidity, and other factors. For example, a forest converted to cropland could have previously contained either large or small quantities of carbon stored above and below the ground. The magnitude of the stored quantity could significantly affect the amount of carbon dioxide released to the atmosphere after conversion. The amount of time that has elapsed since the conversion is also a key factor, because initial loss of carbon tends to be significantly higher than loss in subsequent years. Such distinctions often must be made on a site-by-site basis, requiring a tremendous research effort for the aggregation of data on a national scale.

The IPCC method requires a sequence of steps involving calculations of:

- The net change in above-ground biomass carbon
- The portion of the change that is burned in the first year (either on or off site) versus the amount left to decay over a longer period
- For the burned portion, loss to the atmosphere versus long-term storage in charcoal
- Current emissions from decay of biomass cleared over the previous decade
- Current releases of carbon from soils due to conversions (decomposition of soil organic matter).

The "Missing Sink"

Net carbon flux attributable to U.S. forest land may be significantly higher than estimated in this chapter. Forest researchers have puzzled over a perceived large (2.0 to 3.4 billion tons) unidentified carbon sink in the northern hemisphere. As yet, there have been no definitive answers about what is causing this unidentified carbon sink.

Research is ongoing to characterize carbon flux in U.S. forest land more accurately. One such project is AmeriFlux, a cooperative effort of multiple agencies, sponsored by the U.S. Department of Energy, to better quantify carbon dioxide uptake and release across a spectrum of forest ecosystems. Measurements are being taken by tower gas collection devices employing the "eddy covariance" method. The goal is to measure carbon dioxide uptake and release over long periods of time (i.e., years or decades). The earliest results from the research are not expected for another 4 years.

Converting forests or grasslands to other land uses can have large per-acre effects on greenhouse gas emissions and removals. Forest conversion causes greater changes in greenhouse gas emissions and reductions than grassland conversion. When forests are cleared for development or agriculture, large amounts of carbon dioxide are typically emitted to the atmosphere. For example, average carbon storage (above and below ground) in forests of the Pacific Coast is 205,000 pounds per acre.[84] In contrast, typical estimates of carbon storage in cultivated lands range from a far lower 9,000 to 71,000 pounds per acre.[85]

When grasslands are converted to agricultural use, two effects occur simultaneously: above-ground carbon in the form of biomass may increase, decrease, or remain roughly stable; and below-ground carbon decreases.

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[83] R.A. Birdsey, *Carbon Storage and Accumulation in United States Forest Ecosystems*, USDA Forest Service General Technical Report WO-59 (Washington, DC, August 1992), p. 3.

[84] R.A. Birdsey, *Carbon Storage and Accumulation in United States Forest Ecosystems*, USDA Forest Service General Technical Report WO-59 (Washington, DC, August 1992), p. 3.

[85] See the scattergram in L.K. Mann, "Changes in Soil Carbon Storage After Cultivation," *Soil Science*, Vol. 142, No. 5 (November 1986), p. 284.

The net change in carbon in above-ground biomass depends on the type of crop replacing the grassland species. The default assumption in the IPCC guidelines is that above-ground biomass remains stable when grasslands are converted to crops or pasture.[86] Below-ground carbon, however, virtually always decreases, because soil disturbances during such practices as row-cropping aerate the soil, oxidizing carbon, which is released as carbon dioxide.[87]

Conversion of forest and grasslands to other land uses can also change emissions and absorption of methane and nitrous oxide. The scientific literature suggests that grass and forest lands are both weak natural sinks for methane and weak natural sources of nitrous oxide, although adequate research to establish accurate estimates of aggregate methane and nitrous oxide emissions and sequestration is lacking. Natural soils apparently serve as methane sinks: well-aerated soils contain a class of bacteria called "methanotrophs," which use methane as food and oxidize it into carbon dioxide in small but unquantified amounts.

Experiments indicate that cultivation reduces methane uptake by soils and increases nitrous oxide emissions.[88] Exactly how much methane is absorbed by natural soils, and how much nitrous oxide is emitted, is difficult to estimate, although total amounts are very small. It is known that conversion of forests and grasslands to cropland accelerates nitrogen cycling and increases nitrous oxide emissions from the soil. It is not known with certainty by how much (see Appendix A).[89]

Estimates of forest and grassland conversion in 1997, including estimates of post-conversion land use, are not currently available. The latest national estimates for acreages of different land use types extend only until 1992 (Table 36). Even those estimates lack information called for by the IPCC method; the estimates are limited to land uses upon survey, leaving unanswered the question of what the land was converted *from*. For example, land classified as "urban" increased by 9 million acres between 1980 and 1990;[90] however, the proportions of the land that were previously forest land, grassland, cropland, or some other land use type are unknown. Without such data, it is impossible to quantify accurately greenhouse gas flux due to the conversion to urban land. Similar methodological problems are associated with conversions to other land use types, such as cropland.

An evaluation of the limited data that do exist suggests that forests and grasslands are not being converted to other uses in large quantities. In fact, forest land increased in extent, and grassland remained stable, between 1987 and 1992, the last year for which data are available. Some forest land has been cleared for urban development, but the quantity is small and unquantified. Agricultural land is often more desirable for urban development than forest land because of its proximity to existing population centers and (usually) well-drained, level topography.

Abandonment of Managed Lands

The IPCC category "Abandonment of Managed Lands" includes conversion of cropland, pastureland, or other managed land to unmanaged land. Although included under the IPCC's "Land Use Change and Forestry" section, there is uncertainty as to whether this subcategory will be allowable under national greenhouse gas accounting for purposes of the Kyoto Protocol. Abandoned managed land may revert to forest, grassland, land dominated by shrubs, or any combination of those land types. Under the Kyoto Protocol, only land that reverts to forest is currently reportable, and only if the change to forest is achieved through afforestation or reforestation since 1990. Land that reverted to grassland or other nonforest land would presumably not be reportable under the Kyoto Protocol.

The IPCC guidelines allow for inclusion of abandoned lands that serve as a net sink for carbon accumulation.[91] In the United States, the two most important contributors to this category are lands that have been converted to forested parks, wildlife, and conservation areas; and cropland that has been idled.

It may be possible to count an estimated net 36 million metric tons of carbon sequestered by land included in the "Abandonment of Managed Lands" category in

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[86] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 5.24, web site www.iea.org/ipcc/invs6.htm.

[87] L.K. Mann, "Changes in Soil Carbon Storage After Cultivation," *Soil Science*, Vol. 142, No. 5 (November 1986).

[88] A. Mosier et al., "Methane and Nitrous Oxide Fluxes in Native, Fertilized, and Cultivated Grasslands," *Nature*, Vol. 350, No. 6316 (March 28, 1991), pp. 330-332.

[89] A. Mosier, "Nitrous Oxide Emissions From Agricultural Soils," paper presented at RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control (Amersfoort, The Netherlands, February 3-5, 1993).

[90] A. Daugherty, U.S. Department of Agriculture, Economic Research Service, *Major Uses of Land in the United States: 1992*, Agricultural Economic Report Number 723 (Washington, DC, September, 1995), p. 4.

[91] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 5.34, web site www.iea.org/ipcc/invs6.htm.

1997, almost all of which was sequestered by reserved forest land (in parks, conservation areas, etc.) and forested idled cropland. The precise split in this carbon estimate between reserved and other forests versus idled cropland is not known; however, almost all of the estimated 36 million metric tons was sequestered on reserved forest land, because the forested portion of idled cropland accounted for only 2 million acres in 1992, compared with an estimated 247 million acres of reserved forest land in that year.[92] Although the 2 million acres of forest land in the form of idled cropland would be included in estimates under the IPCC guidelines, the 36 million tons of carbon sequestered on reserved forest land might or might not be included.

Another land use not explicitly included in the Kyoto Protocol but discussed in the IPCC guidelines is wetland drainage. Wetlands emit methane to the atmosphere as a result of anaerobic decomposition of organic matter. The range of observed methane fluxes from U.S. wetlands is enormous. One survey of experiments conducted in the United States found estimates ranging from a negative flux (methane absorption) to a flux of 213 grams of methane per square meter per year, largely dependent on habitat type.[93] Thus, it is difficult to extrapolate from experimental data to large-scale emissions estimates.

Comparisons of estimates of methane fluxes from global wetlands versus temperate zone wetlands alone tend to indicate that methane emissions from temperate-zone wetlands are minimal—typically between 5 and 10 million metric tons of methane per year for worldwide temperate-zone wetlands (which include U.S. wetlands)—when compared with estimated global wetlands emissions of 110 million metric tons.[94] The U.S. share of all temperate-zone wetlands is about 57 percent, and U.S. wetlands lost during the 1980s accounted for about 0.5 percent of the extent of wetlands at the beginning of the decade. Consequently, the reduction in natural methane emissions from U.S. wetlands lost might be on the order of 10,000 to 20,000 metric tons annually over the decade. Conversely, destruction of wetlands may increase atmospheric concentrations of carbon dioxide, which is released after wetland conversion due to aerobic decomposition of organic matter that was formerly under saturated conditions.[95]

Changes in Soil Carbon

The IPCC category "Changes in Soil Carbon" includes changes in soil organic carbon stocks attributable to changes in agricultural land use and management systems.[96] This category may or may not be allowable under the Kyoto Protocol, which limits reporting to activities deemed "measurable and verifiable" and related to ". . . afforestation, reforestation, and deforestation . . . since 1990." The restrictions potentially exclude some or all changes in soil carbon, either because soil carbon is not deemed measurable and verifiable, or because a portion of the accumulation is occurring on land that has not been subject to afforestation, deforestation, or reforestation since 1990, or both.

Because forest soils are such an important carbon sink, serving as the repository for more than half of all carbon on forest lands, USDA Forest Service estimates and projections of soil carbon flux are included under carbon flux on forest land. The ultimate treatment of soil carbon under the Kyoto Protocol is thus a matter of some importance in assessing the potential effects of U.S. adherence to the Protocol.

Changes in soil carbon attributable to changes in agricultural land use and management systems can take on

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[92] The estimated net sequestration of 36 million metric tons in 1997 due to abandonment of managed lands was generated by subtracting net sequestration on timberland from net sequestration on all forest land in 1997, from R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in L.A. Joyce (ed.), *Productivity of America's Forests and Climate Change*, General Technical Report RM-GTR-271 (Fort Collins, CO: USDA Forest Service, 1995). Estimated acres of idled cropland in 1992 are from A. Daugherty, U.S. Department of Agriculture, Economic Research Service, *Major Uses of Land in the United States: 1992*, Agricultural Economic Report Number 723 (Washington, DC, September, 1995), p. 4, modified to account for the estimate that only 4 percent of idled cropland is forested, in J.R. Barker, G.A. Baumgardner, D.P. Turner, and J.J. Lee, "Potential Carbon Benefits of the Conservation Reserve Program in the United States," *Journal of Biogeography* (1995), p. 745.

[93] See E. Matthews and I. Fung, "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics," *Global Biogeochemical Cycles*, Vol. 1, No. 1 (March 1987); and K. Bartlett and R.C. Harriss, "Review and Assessment of Methane Emissions From Wetlands," *Chemosphere*, Vol. 26, Nos. 1-4 (1993), p. 280.

[94] See E. Matthews and I. Fung, "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics," *Global Biogeochemical Cycles*, Vol. 1, No. 1 (March 1987); and K. Bartlett and R.C. Harriss, "Review and Assessment of Methane Emissions From Wetlands," *Chemosphere*, Vol. 26, Nos. 1-4 (1993), p. 280.

[95] T.R. Moore and R. Knowles, "The Influence of Water Table Levels on Methane and Carbon Dioxide Emissions From Peatland Soils," *Canadian Journal of Soil Science*, Vol. 69 (1989), pp. 33-38.

[96] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 5.36, web site www.iea.org/ipcc/invs6.htm.

many forms and can vary widely in magnitude. In general, forests contain the most soil carbon, followed by grasslands, pasture, and rangeland, with cropland containing the least soil carbon. Aside from changes in forest land soil carbon (discussed above), the most significant changes in soil carbon occur when grassland, pasture, or rangeland is converted to or from cropland. Grasslands, pasture, and rangelands all contain significantly more soil carbon than does cropland.

Appendix A
Estimation Methods

The organization of this appendix generally follows the organization of the body of the report: the discussion is divided by greenhouse gas and by emissions source.

Carbon Dioxide

Most U.S. anthropogenic carbon dioxide emissions result from energy consumption. Energy production contributes a small amount from the flaring of natural gas at oil and gas wells, and a number of industrial processes also emit carbon dioxide through noncombustion processes. The largest single source of emissions from these processes is the calcination of limestone in cement production. Other sources include lime manufacture, limestone and dolomite consumption, soda ash manufacture and consumption, industrial carbon dioxide manufacture, and aluminum production. Lastly, some small adjustments are made to reach the total for national emissions. This appendix describes each carbon dioxide emissions source, the estimation methods used, and the data sources.

Several emissions sources are excluded from the carbon dioxide emissions presented in this report, due either to the uncertainty of estimates or because they are based on biomass combustion (which is assumed to be consumed sustainably with a net flux of carbon dioxide to the atmosphere equal to zero). Should the energy use of biomass fuels result in a long-term decline in the total carbon embodied in standing biomass (e.g., forests), the net release of carbon would be treated as a land use issue (see Chapter 6).

Energy Consumption

Emissions Sources

Most U.S. commercial energy is produced through the combustion of fossil fuels, such as coal, natural gas, and petroleum. Chemically, the main components of fossil fuels are hydrocarbons, made up of molecules containing hydrogen and carbon atoms. When these fuels are burned, atmospheric oxygen combines with the hydrogen atoms to create water vapor and with the carbon atoms to create carbon dioxide. In principle, if the amount of fuel burned and the amount of carbon in the fuel are known, the volume of carbon dioxide emitted into the atmosphere can be computed with a high degree of precision. In practice, however, a combination of real-world complexities can reduce the precision of the estimate. These complexities are discussed further in this appendix. Nonetheless, energy-related carbon dioxide emissions are known with greater reliability than are other greenhouse gas emissions sources, and the uncertainty of the estimate is probably 10 percent or less. Appendix C, “Uncertainty in Emissions Estimates,” contains an extended discussion of the nature and sources of uncertainty in the estimates presented in this report.

One real-world complexity is that not all the carbon in fuel is perfectly combusted. About 1.5 percent of the carbon in fossil fuels is emitted in the form of carbon monoxide, which swiftly decays into carbon dioxide in the atmosphere. Another 1 percent is emitted in the form of volatile organic compounds (including methane), which also eventually decay into carbon dioxide. The carbon dioxide emissions reported in Chapter 2 include all “potential” carbon dioxide emissions from the sources covered, including both carbon dioxide emitted directly and carbon emitted in other forms (such as carbon monoxide) that rapidly decay into carbon dioxide in the atmosphere.

Estimation Methods

Carbon emissions in this report were calculated by multiplying energy consumption for each fuel type by an associated carbon emissions coefficient. The result was then modified by subtracting carbon sequestered by nonfuel use. This section describes the derivation of information on energy consumption, emissions coefficients, and carbon sequestered by nonfuel use.

Consumption Data

The Energy Information Administration (EIA) collects a wide variety of information from primary suppliers on a frequent basis and from energy consumers less often, but still in a timely manner. Thus, levels of energy consumption in the United States are fairly well known by end-use sector and detailed fuel type.[97] To estimate carbon dioxide emissions, the EIA uses annual data from the four end-use sectors (residential, commercial, industrial, and transportation) and for all the fossil fuels (coal, natural gas, and the full slate of petroleum products). The petroleum products include asphalt and road oil, aviation gasoline, distillate fuel, jet fuel, kerosene, liquefied petroleum gases (LPG), lubricants, motor gasoline, residential fuel, and other petroleum products. Definitions and chemical characteristics of the fossil fuels are documented in the appendixes of the EIA's recurring reports: the *Annual Energy Review (AER)* and *State Energy Data Report (SEDR)*, as well as the *Petroleum Supply Annual*, *Coal Industry Annual*, and *Natural Gas Annual*. This approach to estimating emissions enables EIA to provide detailed information about trends in sources of emissions.

Information about consumption of "other petroleum" is derived from unpublished EIA data. In recent years, these products have included crude oil, naphtha <401°F, other oil ≥401°F, motor gasoline blending components, miscellaneous products, petroleum coke, pentanes plus, still gas, special naphthas, waxes, and unfinished oils.

Emissions Coefficients

The amount of carbon released when a fossil fuel is burned depends on the density, carbon content, and gross heat of combustion of the fuel.[98] Most of the coefficients for major fuels are assumed to be constant over time. However, for motor gasoline, LPG, jet fuel, and crude oil, EIA developed annualized carbon emissions coefficients to reflect changes in chemical composition or product mix over the years. Appendix B contains a more detailed discussion of the methods employed for developing the coefficients. Table B1 in Appendix B presents a full listing of emissions factors for crude oil, natural gas, and the complete slate of petroleum products.

Corrections to Energy Consumption Information

While, in general, emissions can be estimated simply by multiplying fuel consumption by the appropriate emissions coefficients, several small adjustments to EIA energy statistics are necessary to eliminate double counting or miscounting of emissions. Usually the adjustments amount to less than 0.1 percent of energy-related carbon emissions. They include:

- **Ethanol.** About 70 million barrels of ethanol are included in annual U.S. gasoline consumption after 1992. Because ethanol is a biofuel, the carbon it contains should not be counted as an emission. Hence, carbon from ethanol is deducted from transportation gasoline consumption. Ethanol consumption is reported in the *Renewable Energy Annual* and the *Petroleum Supply Annual*.

- **Synthetic gas from coal.** Small amounts of "supplemental gas"—particularly, gas from the Great Plains Coal Gasification Plant in North Dakota—are manufactured from coal. The coal is counted in industrial energy consumption, and the gas is shipped into the pipeline system. EIA deducts the carbon in synthetic gas (as reported in the *Natural Gas Annual*) from industrial coal emissions.

- **Still gas to pipelines.** Several refineries sell small volumes of "still gas" as supplemental gas to pipelines. EIA deducts the carbon in still gas sales to pipelines (as reported in the *Natural Gas Annual*) from industrial "other petroleum" consumption.

- **Biogas.** The *Natural Gas Annual* reports that small volumes of "supplemental gas" of biological origin (probably landfill gas) are incorporated in U.S. pipeline gas supplies. In keeping with the accounting rule of excluding carbon of biological origin, these supplies are deducted from U.S. natural gas consumption.

- **Carbon dioxide in geothermal steam.** Geothermal steam at The Geysers in Guerneyville, California, where most U.S. geothermal electric power is generated, contains appreciable amounts of carbon dioxide dissolved in the steam, which is released into the atmosphere when the steam is brought to the Earth's surface for power production. EIA includes emissions from this source, at a rate of less than 0.1 million metric tons of carbon per year.

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[97] Although some of EIA's detailed sectoral surveys are conducted only every 3 years on a sample basis, the EIA collects information about apparent consumption of petroleum products (taken as "petroleum product supplied") in mandatory monthly surveys of primary suppliers (e.g., refiners, pipeline operators, importers/exporters, and bulk terminal operators).

[98] Combustion of hydrocarbons results in the production of carbon dioxide, water vapor, and heat. In the United States, the heat resulting from combustion is generally measured as the heat associated with production of water vapor and carbon dioxide. This is commonly referred to as the "higher" or "gross" heating value and is used in EIA statistics on thermal energy. The estimates in this report consistently employ coefficients that reflect the higher heating value assumption. Internationally, however, the "lower" heating value is used. If the lower heating value were used, the Btu content of the fuel would be 5 to 10 percent lower, and the coefficients would be 5 to 10 percent larger, but the carbon emissions estimate would be unchanged. This is sometimes a source of discrepancy. See Organization for Economic Cooperation and Development, *Estimation of Greenhouse Gas Emissions and Sinks*, Final Report (Paris, France, August 1991), pp. 2-12–2-15.

Carbon Sequestration: Nonfuel Use of Fossil Fuels

Gross emissions can be estimated by multiplying fossil fuel consumption by an emissions factor embodying the estimated carbon content of the fuel. However, portions of the fossil fuels consumed are not actually combusted but are used as chemical feedstocks, construction materials, lubricants, solvents, or reducing agents (Table A1). The EIA estimates "nonfuel" use of fossil fuels annually in Table 1.15 of the *Annual Energy Review*.[99] For this report, EIA has gone one step further and determined the fate of the carbon in fuels used for nonfuel purposes (see Table 8 in Chapter 2), based on the rates of sequestration shown in Table A2. In some cases, the carbon winds up in the atmosphere; in other cases, it does not. The principal nonfuel uses of fossil fuels, the methods of estimating nonfuel consumption, and the fate of the carbon are listed below.

- **Natural Gas.** Nonfuel use of natural gas is based on periodic (1985, 1988, 1991, and 1994) reports in EIA's Manufacturing Energy Consumption Survey (MECS). Based on MECS, nonfuel use is divided into three categories: nitrogenous fertilizers, other chemical use, and all other nonfuel uses. Feedstock use of natural gas to make nitrogenous fertilizers is a nonsequestering use, since the underlying chemical in nitrogenous fertilizers is ammonia (NH_3), which is manufactured by steam reforming of natural gas and reacting the synthesis gas with atmospheric nitrogen, leaving the carbon in the feedstock literally "up in the air." In many cases, the carbon dioxide is recovered to make urea or for industrial use. However, carbon in urea and industrial carbon dioxide are generally only temporarily delayed on their way to the atmosphere. EIA assumes that other nonfuel uses in the chemical industry result in 100-percent carbon sequestration. Natural gas is used as a feedstock for a range of chemical products other than ammonia, particularly methanol. Although the methanol used to make methyl tertiary butyl ether (MTBE) winds up in the gasoline pool and is combusted, EIA already counts the carbon in MTBE in gasoline emissions, and to count it again in the feedstock would be double counting. Future research on the fate of the carbon in feedstocks for other chemical industry uses will probably gradually reduce the 100-percent sequestration share currently assumed.

- **Liquefied Petroleum Gases.** Nonfuel use of LPG (ethane, propane, and butane) is estimated on the

Table A1. U.S. Fossil Fuel Consumption for Nonfuel Use, 1990-1997
(Quadrillion Btu)

End Use	1990	1991	1992	1993	1994	1995	1996	P1997
Petroleum								
Asphalt and Road Oil	1.10	1.17	1.08	1.10	1.15	1.17	1.18	1.18
Liquefied Petroleum Gases	1.18	1.20	1.38	1.39	1.35	1.55	1.59	1.70
Pentanes Plus	0.08	0.08	0.04	0.06	0.28	0.26	0.30	0.32
Lubricants	0.35	0.36	0.32	0.33	0.34	0.35	0.35	0.34
Industrial	0.18	0.19	0.17	0.17	0.17	0.18	0.18	0.17
Transportation	0.17	0.18	0.16	0.16	0.16	0.17	0.17	0.16
Petrochemical Feed	0.96	1.12	1.15	1.20	1.22	1.26	1.21	1.20
Petroleum Coke	0.14	0.18	0.16	0.25	0.17	0.18	0.19	0.21
Special Naphtha	0.11	0.11	0.09	0.10	0.10	0.08	0.07	0.07
Other (Waxes and Misc.)	0.23	0.22	0.25	0.20	0.19	0.20	0.19	0.19
Coal	0.02	0.02	0.02	0.04	0.03	0.03	0.03	0.03
Natural Gas to Chemical Plants	0.58	0.59	0.59	0.61	0.63	0.69	0.71	0.76
Total	**4.66**	**4.98**	**5.04**	**5.23**	**5.18**	**5.51**	**5.52**	**5.68**

P = preliminary data.

Notes: Asphalt and lubricants are as reported in the EIA's *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, September 1997) for 1989-1995, and *Monthly Energy Review*, DOE/EIA-0035(98/07) (Washington, DC, July 1998) for 1996 and 1997. Some slight differences exist between this table and the *Annual Energy Review*. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Source: Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), Table 1.16, p. 35, and underlying estimates.

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[99] Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), p. 33.

Table A2. Rates of Sequestration for U.S. Fossil Fuel Consumption

Fuel Type	Fraction of Fuel Combusted	Fraction of Nonfuel Use of Energy Sequestered
Petroleum		
Motor Gasoline	0.990	--
LPG	0.995	0.80
Jet Fuel	0.990	--
Distillate Fuel	0.990	0.50
Residual Fuel	0.990	0.50
Asphalt and Road Oil	0.990	1.00
Lubricants	0.990	0.50
Petrochemical Feed	0.990	0.75
Aviation Gas	0.990	--
Kerosene	0.990	--
Petroleum Coke	0.990	0.50
Special Naphtha	0.990	0.00
Other		
Aviation Gas Blending Components	0.990	--
Crude Oil	0.990	--
Naphtha <401°F	0.990	0.75
Other Oil ≥401°F	0.990	0.50
Petrochemical Feed Still Gas	0.990	0.80
Motor Gasoline Blending Components	0.990	--
Miscellaneous	0.990	1.00
Natural Gasoline	0.990	--
Plant Condensate	0.990	--
Pentanes Plus	0.990	0.80
Still Gas	0.995	--
Special Naphthas	0.990	0.00
Unfinished Oils	0.990	--
Unfractionated Stream	0.990	--
Waxes	0.990	1.00
Coal		
Residential and Commercial	0.990	--
Industrial Coking	0.990	0.75
Industrial Other	0.990	--
Electric Utility	0.990	--
Natural Gas		
Flare Gas	1.000	--
Natural Gas	0.995	0.29-0.52
Crude Oil	0.990	--

Sources: EIA estimates documented in this chapter; and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.28-1.29, web site www.iea.org/ipcc/invs6.htm.

basis of sales of these products to the chemical industry, as reported by the American Petroleum Institute (API) in its annual survey, *Sales of Natural Gas Liquids and Liquefied Refinery Gases*, from which EIA deducts chemical industry fuel use of LPG as reported periodically in the MECS. Most of the ethane, propane, and butane used by the chemical industry is used to manufacture ethylene, propylene, and butadiene, respectively, all of which are intermediate products for plastics. Following the recommendation of the Intergovernmental Panel on Climate Change (IPCC), EIA assumes that 80 percent of nonfuel use is sequestered in plastics, synthetic rubber, and related products.[100]

- **Asphalt and Road Oil.** EIA assumes that asphalt and road oil use is nonfuel use by definition, and that all carbon in asphalt and road oil is sequestered.

- **Pentanes Plus.** "Pentanes plus" are hydrocarbons heavier than butane extracted from natural gas at gas processing plants. Their principal uses are as contributors to the gasoline pool and as petrochemical feedstocks. Nonfuel use of pentanes plus is estimated on the basis of the API's annual survey of natural gas liquids and refinery gases sold to the chemical industry. Following IPCC practice for LPG, EIA assumes that 80 percent of the carbon in pentanes plus used by the chemical industry is sequestered.

- **Petrochemical Feedstocks.** The EIA's petroleum surveys recognize two categories of products called "petrochemical feedstocks." These are presumably naphtha and gas oils destined for ethylene crackers, and probably some mix of aromatic hydrocarbons (benzene, toluene, and xylene) and feedstocks used to make aromatic hydrocarbons. All petrochemical feedstock supplies are included in nonfuel use by definition, and, following the practice of the IPCC, EIA assumes that 75 percent of the carbon in synthetic feedstocks and 50 percent of the carbon in gas oil feedstock is sequestered in plastics, synthetic fibers, and related products.

- **Distillate and Residual Fuels.** The MECS reports small volumes (10 million barrels and 1 million barrels, respectively) of distillate and residual oils used for nonfuel purposes in the chemical industry. Following the practice for gas oil petrochemical feedstocks, EIA assumes 50-percent sequestration. Future research may shed more light on the industrial processes that use these fuels.

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[100] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, web site www.iea.org/ipcc/invs6.htm.

- **Petroleum Coke.** Petroleum coke is a coal-like solid, about 90 percent carbon by weight, created after intensive extraction of lighter hydrocarbons from petroleum feedstocks by oil refiners. Most petroleum coke is used in the refineries as fuel or as a catalyst. EIA estimates nonfuel use by taking the quantity of petroleum coke supplied and deducting all known fuel uses (refinery use from the *Petroleum Supply Annual*, electric utility use from the *Electric Power Annual*, and industrial use from the MECS). EIA assumes that 50 percent of the carbon in petroleum coke for nonfuel use is sequestered. It should be noted, however, that significant sequestering nonfuel uses of petroleum coke in the United States are difficult to identify. The principal identified nonfuel use is for sacrificial anodes in primary aluminum smelting, a nonsequestering use that EIA counts separately under process emissions (see the next section). It appears that petroleum coke is also used in small quantities by many different industries as a reducing agent (a source of carbon monoxide that, in turn, can be used to scour oxygen from products such as lead oxide (to produce lead) or iron oxide (to produce iron). These are, however, nonsequestering uses.

- **Still Gas.** Still gas is the gas that floats to the top of distillation columns in oil refineries. Its chemical composition is a highly variable blend of free hydrogen, methane, carbon monoxide, and heavier hydrocarbons, depending on the refinery process, the feedstock, and process conditions. EIA estimates nonfuel use by deducting all known fuel uses (refinery fuel use from the *Petroleum Supply Annual* and pipeline gas supplies from the *Natural Gas Annual*). The remainder is assumed to be dispatched to chemical plants as a feedstock. Following the IPCC practice for LPG, EIA assumes that 80 percent of the carbon in still gas is sequestered.

- **Special Naphtha.** "Special naphtha" is a catch-all for an array of hydrocarbon-based solvents, such as hexane and the volatile oils used in petroleum-based paint. In general, solvents evaporate into the atmosphere as "nonmethane volatile organic compounds" after use and swiftly weather into atmospheric carbon dioxide. EIA assumes that all special naphthas are for nonfuel use and that no carbon in special naphtha is sequestered.

- **Lubricants.** The most common petroleum-based lubricant is motor oil, but the category also includes numerous other products, such as industrial greases. Following the IPCC, EIA assumes that 50 percent of the carbon in lubricants is sequestered. The ultimate fate of lubricants is not easy to determine. For example, it is often the case that "recycling" motor oil means burning it as boiler fuel.

- **Waxes and Polishes.** The principal use of waxes is to make wax paper and food packaging materials, which usually end up in landfills. Following the IPCC, EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for these materials.

- **Miscellaneous.** EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for this category.

- **Coal.** Arguably, the manufacture of coke is the largest nonfuel use of coal. By convention, however, coke manufacture is treated as a fuel use. This is not unreasonable, because coke is almost always ultimately combusted. Coke is manufactured by "cooking" high-grade coal in huge ovens in the absence of oxygen. Volatile materials, moisture, and certain categories of impurities are driven off, leaving behind a high-carbon material suitable for metallurgical use. Among the byproducts of the process are "coal tars" or "coal liquids," which typically are rich in aromatic hydrocarbons, such as benzene. Coal tars generally are used as feedstocks in the chemical industry. "Nonfuel use" of coal, as defined for this report, consists of the coal tars driven off during the manufacture of coke. Coal tar production was obtained, for years prior to 1995, from the International Trade Commission's *Synthetic Organic Chemicals*. Since 1995, production has been estimated on the basis of the ratio of 1994 coke production to coal tar production. Following the IPCC guidelines, EIA assumes that 75 percent of the carbon in coal tars is sequestered.

Carbon Sequestration: Fraction Combusted

A small amount of carbon sequestration is associated with the combustion of fossil fuels. Using IPCC assumptions, EIA assumes that oxidation of liquid and solid fuels during combustion is 99 percent complete, and that 1 percent of the carbon remains sequestered. Oxidation of gaseous fuels (LPG and natural gas) is assumed to be 99.5 percent complete.[101] Conceptually, fuel may be "lost" before combustion due to evaporation, leaks, or spills; it may be subject to incomplete combustion and vented to the atmosphere in the form of volatile organic compounds or particulates; or it may remain at the site of combustion in the form of carbon-containing ash or soot.

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[101] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.29, web site www.iea.org/ipcc/invs6.htm.

Data Sources

Fossil Fuel Consumption (1980-1995): Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, September 1997). **(1996-1997):** Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(98/07) (Washington, DC, July 1998); *Petroleum Supply Annual 1997*, DOE/EIA-0340(97) (Washington, DC, June 1998); *Natural Gas Annual 1996*, DOE/EIA-0131(96) (Washington, DC, October 1997); and *Renewable Energy Annual 1997*, DOE/EIA-0603(97) (Washington, DC, March 1998).

Nonfuel Use of Energy and Biofuels Consumption: Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-384(97) (Washington, DC, July 1998); Energy Information Administration, *Manufacturing Energy Consumption Survey 1991*, DOE/EIA-0512(91) (Washington, DC, December 1994); Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), and previous years (1985, 1988, and 1991); American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gas* (various years); U.S. International Trade Commission, *Synthetic Organic Chemicals*, USITC Publication 2933 (various years through 1994); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, web site www.iea.org/ipcc/invs6.htm.

Adjustments to U.S. Energy Consumption

In recent years, there have been several estimates of U.S. carbon emissions, some of which differ by as much as 5 percent. Two significant reasons for the differences in emissions estimates (beyond those associated with differences in coefficients) are the definitions of “energy consumption” and “the United States” employed by researchers. Subtle differences in definition can produce variations of several percentage points in reported energy consumption and, hence, in carbon emissions. Some estimates include U.S. territories while others exclude them. If consumption is estimated as “apparent consumption” based on production plus imports minus exports plus stock change, then statistical discrepancies will be included in consumption. International bunkers are sometimes counted as domestic consumption and sometimes as exports. This section describes how each adjustment is accommodated in the EIA estimates.

U.S. Territories

Emissions Sources

EIA’s energy data for the United States cover only the 50 States and the District of Columbia. In contrast, energy data produced by the International Energy Agency for the United States cover the 50 States plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, Guam, American Samoa, Micronesia, and Wake Island. Annual energy consumption in the U.S. territories is only about 0.5 quadrillion Btu (Table A3).

Table A3. Energy Consumption in U.S. Territories and International Bunkers, 1990-1997
(Quadrillion Btu)

Place	1990	1991	1992	1993	1994	1995	1996	P1997
U.S. Territories								
Puerto Rico	0.31	0.30	0.37	0.32	0.33	0.35	0.32	0.31
Virgin Islands	0.12	0.11	0.12	0.11	0.13	0.13	0.16	0.16
American Samoa	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Guam	0.01	0.03	0.03	0.02	0.05	0.06	0.05	0.05
Micronesia	*	*	*	*	*	*	*	*
Wake Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	**0.47**	**0.47**	**0.55**	**0.49**	**0.54**	**0.58**	**0.57**	**0.55**
U.S. Bunker Fuels	1.06	1.05	1.11	1.17	1.06	1.03	1.09	1.04

*Less than 5 trillion Btu.

P = preliminary data.

Notes: Energy consumption in Micronesia ranged from 0.002 to 0.004 quadrillion Btu. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Sources: **U.S. Territories:** Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in “Other” countries in the Asia/Pacific region. Data are shown in tables of “Apparent Consumption of Petroleum Products.” Data for 1997 based on unpublished preliminary information. **Bunker Fuels:** Jet Fuel—Oak Ridge National Laboratory, *Transportation Energy Data Book* (Oak Ridge, TN, various years); Distillate and Residual Fuel Oils, 1987-1990—Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, 1987-1990); Distillate and Residual Fuel Oils, 1991-1997—Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, 1991-1997).

Because all the U.S. territories are islands, their consumption consists primarily of petroleum products. For the territories as a group, oil consumption ranges between 200,000 and 250,000 barrels per day, and coal consumption averages about 300,000 short tons per year, mostly in Puerto Rico.

Estimation Methods

Energy consumption for U.S. territories is converted to carbon emissions by using the same emissions coefficients applied to U.S. energy data. Carbon emissions for U.S. territories range from 10 to 12 million metric tons per year (see Table 6 in Chapter 2). Because a large portion of reported energy consumption in U.S. territories is from "other petroleum," there is a degree of uncertainty about the correct emissions factor to be used in this area, as well as the reliability of underlying data.

Data Sources

1980-1996: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, various years), and unpublished estimates for Wake Island, American Samoa, and the Pacific Trust Territories, which are included as "Other" in the Far East and Oceania region in the *International Energy Annual*. **1997:** EIA estimate.

International Bunker Fuels

Emissions Sources

The term "international bunker fuels" refers to fuel purchased by merchant ships in U.S. ports and by international air carriers in U.S airports. By convention, trade statistics treat sales of bunker fuels as exports by the selling country, because the purchaser promptly hauls the fuel outside national boundaries. This convention is followed by organizations that prepare international energy statistics, such as the United Nations and the International Energy Agency.

Bunker fuels, however, are an export without a corresponding import, because the purchasing ship generally burns the fuel on the high seas. EIA energy statistics, which are based on domestic sales of products, treat bunker fuels sales in the same way as sales of other fuels, i.e., as domestic energy consumption. Carbon emissions from bunker fuels are, therefore, already counted in the domestic energy consumption of the United States—primarily as transportation-related consumption of residual oil. Those who wish to understand the differences between emissions inventories based on international energy statistics and EIA data will, however, need to know the amount of energy consumption and the amount of carbon emissions associated with international bunkers. Table A3, therefore, shows U.S. international bunker fuel usage.[102] The amount is about 1.1 quadrillion Btu (or 500,000 barrels per day), largely of residual oil. It accounts for emissions of about 19 to 24 million metric tons of carbon annually (see Table 6 in Chapter 2).

Estimation Methods

The appropriate carbon coefficient is applied to estimated annual consumption for several fuels (including residual and distillate fuels, as well as kerosene-type jet fuels), with the assumption that 99 percent of the fuel is combusted.

Data Sources

Distillate and Residual Fuels (1980-1990): Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, 1980-1990). **(1991-1997):** Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, 1991-1997). **Jet Fuels (1980-1996):** Oak Ridge National Laboratory, *Transportation Energy Data Book* (Oak Ridge, TN, various years). **1997:** EIA estimate.

Industrial Sources

Carbon dioxide emissions from "industrial sources" are industrial emissions that are not caused by the combustion or feedstock use of commercial fossil fuels. These emissions typically are created either by the combustion of waste products containing fossil carbon (natural gas flaring) or by chemical reactions with carbon-containing minerals (for example, calcining sodium carbonate [limestone] to make lime or cement).

Energy Production

Emissions Sources

U.S. energy production also generates small volumes of carbon dioxide emissions. The two principal sources are flaring of natural gas and venting of carbon dioxide

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[102] Up to 1990, bunker fuel consumption was reported by the U.S. Department of Commerce on the basis of trade data. Since 1991, bunker fuel data have been collected by the EIA on the basis of sales of specialized marine fuels by wholesalers. These data do not distinguish between international and domestic bunker fuel, nor do they provide for aviation bunkers. For recent years, international aviation bunkers and international marine bunkers are estimated on the basis of computations made by Oak Ridge National Laboratory in its *Transportation Energy Data Book*, Edition 13, p. A-5. International bunkers are assumed to account for 25 percent of marine distillate sales, 75 percent of marine fuel oil sales, and 15 percent of kerosene-based jet fuel sales.

produced in conjunction with natural gas.[103] When a field is developed for petroleum extraction, any natural gas associated with that field may be flared if its use is not economically justifiable. This is typically the case for remote sites or when the gas is of poor quality or minimal volume. During natural gas production, flaring may be used for disposal of waste products (e.g., hydrogen sulfide), capacity testing, or as a result of process upsets.

Emissions from the second source, carbon dioxide produced in conjunction with natural gas, occur during production activities. Natural gas is actually a mixture of several different gases including carbon dioxide. If the carbon dioxide content of natural gas is large enough to reduce the heating value of the gas below the specification for pipeline gas (870 Btu per standard cubic foot), the carbon dioxide is typically extracted by amine scrubbing. The extracted carbon dioxide generally is released to the atmosphere.

Estimation Methods

The method for estimating emissions from natural gas flaring is based on the volume of vented and flared gas reported to the EIA (assuming that all gas is flared). To calculate carbon emissions, the figures are aggregated, converted into Btu, and then multiplied by an emissions coefficient of 14.92 million metric tons of carbon per quadrillion Btu.

As estimates presented in Chapter 2 indicate, natural gas flaring is a minor source of emissions, accounting for only about 2 to 5 million metric tons of carbon annually. There is some uncertainty associated with this estimate, given that operators in the field are not required to meter gas that is vented or flared.

The carbon dioxide produced in conjunction with natural gas is estimated by multiplying regional production data by regional carbon dioxide contents from a Gas Research Institute (GRI) study. The estimates of carbon dioxide emitted during transmission and distribution are derived by multiplying pipeline and end-use consumption data by the carbon dioxide content of natural gas delivered to consumers from a second GRI study. Emissions associated with production activities are calculated by subtracting consumption-related emissions from the total carbon dioxide initially produced.

Data Sources

Flaring (1980-1996): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). **(1997):** *Natural Gas Monthly*, DOE/EIA-0130(98/06) (Washington, DC, June 1998). **Carbon Dioxide Produced with Natural Gas: Composition (1980-1997):** Gas Research Institute, *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States—1993 Update*, GRI-93/0456.1. Gas Research Institute, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*, GRI-92/0123. **Production (1980-1996):** Dwight's Energy Data Lease/Well Production File. **(1997):** Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130 (Washington, DC, 1997). **Transmission and End-Use Consumption (1980-1996):** Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). **(1997):** Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130 (Washington, DC, 1998).

Industrial Processes

In addition to energy-related emissions, carbon dioxide is also produced during certain industrial processes. The primary source of industrial emissions is the calcination of limestone ($CaCO_3$) to create lime (CaO). These two compounds are basic materials in a variety of manufacturing processes, particularly cement, iron and steel, and glass. Other sources of industrial emissions include the production and use of soda ash (Na_2CO_3), the manufacture of carbon dioxide, and aluminum production.

For this source category, emissions estimates are based on the compound used in the industrial process. Table A4 shows activity data for industrial processes. By multiplying the amount of production or consumption of the compound by a carbon coefficient (the relative amount of carbon in that compound), a process-specific estimate is derived. In recent years, industrial sources have accounted for about 17 to 18 million metric tons of carbon annually. Each industrial process, emissions source, and estimation method is discussed below.

Cement Manufacture

More than half of the carbon dioxide emissions from industrial sources originate from cement manufacturing (see Chapter 2).

Emissions Sources. Four basic materials are required to make cement: calcium, silicon, aluminum, and iron. Substrates of these materials are ground into a powder and heated in a kiln. While in the kiln, limestone (the predominant source of calcium) is broken down into carbon dioxide and lime. The carbon dioxide is driven off into the atmosphere. After the kilning process has been completed, cement clinker is left.

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[103] See discussion of carbon dioxide manufacture for the treatment of vented carbon dioxide.

Table A4. Production Data for Industrial Sources of Carbon Dioxide, 1990-1997
(Thousand Metric Tons)

Item	1990	1991	1992	1993	1994	1995	1996	P1997
Cement Clinker	63,326	61,608	62,184	65,745	69,787	69,983	70,361	71,811
Masonry Cement	2,911	2,592	2,806	2,962	3,613	3,603	3,469	3,533
Lime Produced	15,832	15,667	16,199	16,932	17,300	18,500	19,100	19,300
Limestone in Iron Smelting	3,955	3,635	3,098	2,561	2,538	2,615	2,538	2,764
Limestone in Steelmaking	682	738	612	1,087	1,225	1,126	949	750
Limestone in Glass	255	269	354	439	482	598	691	691
Limestone in FGD	4,369	4,606	4,479	4,274	5,080	6,396	6,740	6,740
Dolomite	687	732	641	549	601	428	450	450
Soda Ash Production	8,147	8,152	8,269	8,051	8,111	9,167	9,056	9,500
Soda Ash in Glass	3,177	2,997	3,082	3,095	3,150	3,130	3,040	3,130
Soda Ash in FGD	179	155	156	146	191	211	206	206
Sodium Silicate	740	789	838	913	1,008	1,066	973	973
Sodium Tripolyphosphate	451	419	399	426	423	426	426	426
Aluminum Manufacture	4,048	4,121	4,042	3,695	3,299	3,375	3,577	3,600
Copper Primary Smelting	1,577	1,580	1,710	1,790	1,840	1,930	2,010	2,070

P = preliminary data.

Sources: U.S. Department of the Interior,Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years). U.S. Department of the Interior, United States Geological Survey, *Cement Annual Report* (Washington, DC, various years). American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years). U.S. Department of the Interior, Geological Survey, *Soda Ash Annual Report* (Washington, DC, various years) (soda ash production calculated from quantity of trona ore production). U.S. Department of the Interior, Geological Survey, *Crushed Stone Annual Report* (Washington, DC, various years). Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1997* (Washington, DC, September 1997). Energy Information Administration unpublished survey data, *Steam Electric Plant Operation and Design Report, Form EIA-767* (Washington, DC, various years). Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994).

Estimation Methods. One mole of calcined limestone produces one mole of carbon dioxide and one mole of lime. Since virtually all of the lime produced is absorbed into the clinker, the lime content of clinker is assumed to be representative of the amount of carbon dioxide emitted. In order to estimate emissions from cement manufacture, a carbon coefficient must be calculated. The EIA has adopted the IPCC recommendation that 64.6 percent of cement clinker is lime.[104] Multiplying this lime content factor by the ratio of carbon produced to lime produced yields the coefficient for cement clinker. A separate coefficient is necessary for estimating emissions from the additional lime used to produce masonry cement. In this case, the amount of lime not accounted for as clinker is assumed to be 3 percent.[105] This factor is then multiplied by the same production ratio of carbon to lime, generating the carbon coefficient for masonry cement.

Lime Manufacture

Lime is an important chemical with a variety of industrial, chemical, and environmental applications.

Emissions Sources. Lime production involves three main stages: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone is roasted at high temperatures, just as it is released during clinker production. The carbon dioxide is driven off as a gas and normally exits the system with the stack gas.

Estimation Methods. Based on the ratio of the molecular weight of carbon dioxide to the weight of calcium carbonate, the EIA assumes that 785 metric tons of carbon dioxide, or 214 metric tons of carbon, are released for every 1,000 metric tons of lime produced. This factor is applied to annual levels of lime manufacture to estimate potential emissions. The EIA does not account for the instances in which the carbon dioxide is recovered or reabsorbed. Representatives of the National Lime Association believe that 10 to 20 percent of the carbon dioxide emitted in lime manufacture is recovered for industrial use or reabsorbed from the atmosphere by chemical reactions induced by the use of lime.

[104] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, web site www.iea.org/ipcc/invs6.htm.

[105] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993* (Washington, DC, 1994), p. 32.

Limestone and Dolomite Consumption

These are basic raw materials used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries.

Emissions Sources. Limestone (including dolomite) can be used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems in utility and industrial plants, or as a raw material in glass manufacturing. Limestone is heated during these processes, generating carbon dioxide as a byproduct.

Estimation Methods. Assuming that limestone has a carbon content of 12 percent and dolomite 13.2 percent, the EIA applies the appropriate factor to the annual level of consumption in the iron smelting, steelmaking, and glass manufacture industries, and in flue gas desulfurization systems that use this sorbent. This amounts to 120 metric tons of carbon for every 1,000 metric tons of limestone consumed, or 132 metric tons of carbon for every 1,000 tons of dolomite consumed (when dolomite is distinguished in the data).

Soda Ash Manufacture and Consumption

Commercial soda ash (sodium carbonate) is used in many familiar consumer products, such as glass, soap and detergents, paper, textiles, and food.

Emissions Sources. Two methods are used to manufacture natural soda ash in the United States. The majority of production comes from Wyoming, where soda ash is manufactured by calcination of trona ore in the form of naturally occurring sodium sesquicarbonate. For every mole of soda ash created in this reaction, one mole of carbon dioxide is also produced and vented to the atmosphere. The other process used to manufacture soda ash is carbonation of brines; however, the carbon dioxide driven off in this process is captured and reused.

Once manufactured, most soda ash is consumed in glass and chemical production. Other uses include water treatment, flue gas desulfurization, soap and detergent production, and pulp and paper production. As soda ash is processed for these purposes, additional carbon dioxide may be emitted if the carbon is oxidized. Because of the limited availability of specific information about such emissions, only certain uses of soda ash are considered in this report. Sodium silicate and sodium tripolyphosphate are included as chemicals manufactured from soda ash and components of detergents.

Estimation Methods. For soda ash manufacture, in order to ensure that carbon dioxide from the carbonation of brines is not included in emissions estimates, the calculations in this report are derived solely from trona ore production figures. Approximately 1.8 metric tons of trona ore are required to yield 1 metric ton of soda ash. This amounts to 97 million metric tons of carbon for every 1,000 tons of trona ore produced annually. For soda ash consumption, the EIA applies a factor of 113 metric tons of carbon for every 1,000 metric tons of soda ash consumed in glass manufacturing or in flue gas desulfurization.

Carbon Dioxide Manufacture

Emissions Source. Carbon dioxide is produced from a small number of natural wells and as a byproduct of chemical (i.e., ammonia) manufacturing. The Freedonia Group has determined that, in the United States, there is an 80 percent to 20 percent split between carbon dioxide produced as a byproduct and carbon dioxide produced from wells.[106] Emissions of byproduct carbon dioxide are incorporated into the natural gas energy consumption estimates as nonfuel, nonsequestered carbon and therefore are not included here to avoid double counting.

Most carbon dioxide produced from wells is injected back into the ground for enhanced oil recovery. This process sequesters the carbon dioxide, at least in the short run. Conceptually, only carbon dioxide produced from wells and diverted to industrial use is emitted to the atmosphere.

Estimation Methods. The Freedonia Group estimates that nonsequestering industrial use of carbon dioxide resulted in emissions of 1.3 million metric tons of carbon in 1993.[107] If 20 percent of this industrial use is supplied by wells, emissions can be estimated at 0.26 million metric tons of carbon. Based on the Freedonia report, the 1997 estimate is calculated by assuming an annual 4.2-percent increase, implying emissions of 0.31 million metric tons of carbon.

Aluminum Manufacture

Aluminum is an element used in alloys. Because it is light in weight, malleable, and not readily corroded or tarnished, it is used as a principal material for kitchen utensils, aircraft, some automobiles, bicycles, and other manufactured products. The United States is a major producer of aluminum and also an importer, depending on market conditions.

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[106] The Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), p. 46.
[107] The Freedonia Group, Inc., *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994), p. 37.

Emissions Sources. As part of the primary aluminum smelting process, alumina (aluminum oxide, Al_2O_3) is vaporized by a powerful electric current. Emissions from the electricity used to generate the current are included with emissions from industrial electricity consumption and are not counted separately. The current also vaporizes a carbon "sacrificial anode," typically manufactured from petroleum coke. This is a nonsequestering nonfuel use of a fossil fuel. To avoid double counting, 50 percent of nonfuel use of petroleum coke is carried as "sequestering." Thus, process emissions from aluminum smelting can be considered as a deduction from the sequestering portion of nonfuel use of petroleum coke.

Estimation Methods. In previous years, following the work of Abrahamson, EIA has used the midpoint of a range of emissions factors of 1.5 to 2.2 metric tons of carbon dioxide (0.41 to 0.60 metric tons of carbon) emitted per metric ton of aluminum smelted.[108] The 1994 MECS indicated that nonfuel use of fuels by aluminum smelters (SIC 3334) totaled 40 trillion Btu in 1994.[109] The composition of nonfuel use by fuel type has been withheld for confidentiality purposes, but it is probable that most of the 40 trillion Btu consists of petroleum coke, which would imply an emissions factor of about 0.338 metric tons of carbon per metric ton of aluminum smelted (0.04 quadrillion Btu of coke × 27.85 million metric tons of carbon per quadrillion Btu / 3.295 million metric tons of aluminum smelted in 1994). EIA now uses an emissions factor of 0.4 metric tons carbon per metric ton of aluminum smelted, which is at the low end of Abrahamson's range and also equals the mass balance for a "typical" aluminum smelter from another source.[110]

Data Sources for Industrial Processes

The U.S. Geological Survey reports listed below can be found on the Internet at minerals.er.usgs.gov/pubs/commodity.

Cement and Clinker Production (1980-1996): U.S. Department of the Interior, U.S. Geological Survey, *Cement Annual Report* (Washington, DC, various years). **(1997):** U.S. Department of the Interior, U.S. Geological Survey, Office of Minerals, Faxback Service.

Lime Manufacture: (1980-1997): U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years).

Limestone Consumption in Iron Smelting, Steelmaking, and Glass Manufacture: (1980-1996): U.S. Department of the Interior, U.S. Geological Survey, *Crushed Stone Report* (Washington, DC, various years). **(1997):** EIA estimate. **Limestone Consumption in Flue Gas Desulfurization: (1980-1995):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years).

Soda Ash Manufacture and Soda Ash Consumption in Glass Making (1980-1997): U.S. Department of the Interior, U.S. Geological Survey, *Soda Ash Report* (Washington, DC, various years). **Soda Ash Consumption in Flue Gas Desulfurization (1980-1996):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(1997):** EIA estimate. **Sodium Silicate and Sodium Tripolyphosphate: (1980-1996):** Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1997* (Washington, DC, September 1997), pp. 37-38. **(1997):** EIA estimate.

Carbon Dioxide: Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994).

Aluminum (1980-1997): U.S. Department of the Interior, U.S. Geological Survey, *Aluminum Report* (Washington, DC, various years).

Methane

Energy Sources

Oil and Gas Production, Processing, and Distribution

Emissions Sources

Because methane is the principal constituent of natural gas (representing about 95 percent of the mixture), releases of natural gas result in methane emissions. Methane emissions can be grouped into three categories: (1) fugitive or unintentional leaks emitted from sealed surfaces such as pipelines, gaskets, and flanges; (2) vented or intentional releases from process vents, maintenance blowdowns, and pneumatic devices; and

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[108] D. Abrahamson, "Aluminum and Global Warming," *Nature*, Vol. 356 (April 1992), p. 484.

[109] Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3, p. 49.

[110] Drexel University Project Team, *Energy Analysis of 108 Industrial Processes* (Lilburn, GA: The Fairmont Press, 1996), p. 282.

(3) releases from incomplete combustion in compressor engines, burners, and flares.[111] The natural gas industry can be divided into four source segments:

- **Gas Production.** This segment consists of gas and oil wells, surface equipment to produce gas, and gathering pipeline. Leakage occurs from valves, meters, and flanges. Pneumatic valves release gas when they are reset. Gathering pipeline may be emptied for maintenance or may have fugitive emissions.
- **Gas Processing.** When gas is processed, liquefied petroleum gases and natural gasoline are removed for sale or further refining. Water is also removed, and gas is conformed to commercial pipeline quality and heat content. Methane is released during maintenance, via leaks, and during system upsets when sudden increases in pressure require a gas release or result in a system rupture.
- **Transmission and Storage.** High-pressure transmission pipelines are used to transport natural gas from production fields and gas processing facilities to distribution pipelines. Natural gas may escape through leaky pipes and valves. Methane may be emitted as part of compressor exhaust. Gas is often stored near consumption centers to meet peak demand during periods of high consumption. These storage facilities emit methane in compressor exhaust and from dehydrators.
- **Distribution.** The pressure of gas received from the transmission system is lowered at the gate station and is forwarded to distribution pipeline for delivery to residential, commercial, and industrial consumers. Leaks may occur at gate stations, through leaky pipes, and at customer meters.

Methane may also be emitted during *oil refining and transportation*. These emissions occur when methane is separated from crude oil during refining. After oil is transferred to storage tanks methane may be emitted by vapor displacement. Vapor displacement also occurs during loading and unloading of oil barges and tankers.

Estimation Methods

Natural Gas Systems. Previous EIA estimates of emissions from the natural gas system were scaled to commonly available activity data such as number of wells in operation, miles of gathering pipeline, gas throughput, gas volumes processed, miles of transmission pipeline and miles of distribution pipeline. The activity data were multiplied by emissions factors derived from point-in-time emissions estimates for 1992 developed in a study sponsored jointly by the U.S. Environmental Protection Agency (EPA) and the Gas Research Institute (EPA/GRI).[112] The EPA/GRI study, however, provides activity data and disaggregated emissions factors for 86 separate gas industry process components. In an effort to take advantage of this level of detail, this report estimates the number of each process component for the years 1990-1997. Each process component is scaled to a widely available metric, such as gas withdrawals or pipeline miles most related to the process activity. The derived activity data are then applied to the component emissions factor from the EPA/GRI report.

Oil Wells. The number of operating oil wells in the United States is multiplied by a per-well emissions factor from the EPA's report to Congress, *Anthropogenic Methane Emissions in the United States*.[113]

Oil Refining and Transportation. Estimates are calculated by using emissions from a 1992 Radian Corporation report[114] in conjunction with refinery data collected by EIA.

Data Sources

Natural Gas Systems. Emission factors and activity data for 1992 are from the joint EPA/GRI study: National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996). Activity data for all other years are scaled to data from the following sources: gas wellheads, gross gas withdrawals, gas processing and gas removed from storage can be found in EIA's *Natural Gas Annual* (various years); transmission and distribution pipeline mileage are published annually by the American Gas Association in *Gas Facts*.

Oil Wells. The number of operating oil wells is available annually in the February issue of the *World Oil* journal.

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[111] National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), p. 19.

[112] National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), p. 19.

[113] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, Report to Congress (Washington, DC, April 1993), p. 2-22.

[114] Radian Corporation, *Global Emissions of Methane From Petroleum Sources*, Prepared for the American Petroleum Institute (Research Triangle Park, NC, February 1992), Table A-1, p. A-1.

Oil Refining and Transportation. Data on the volume of crude oil refined and the volume of crude oil transported on marine vessels can be found in EIA's *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years), and *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Coal Mining

Emissions Sources

As coal is formed from organic material by natural chemical and physical processes, methane is also produced. The methane is stored in the pores (open spaces) of the coal itself and in cracks and fractures within the coalbed. As coal is mined, the pressure surrounding the stored methane decreases, allowing much of it to be released into the operating coal mine (in the case of an underground mine) or into the atmosphere (in the case of a surface mine). The methane remaining in the coal pores is emitted when the coal is transported and pulverized for combustion. There are five avenues for methane emissions from coal mines:

- **Ventilation Systems in Underground Mines.** Methane in concentrations over 5 percent is explosive and presents a mortal danger to coal miners. To meet safety standards set by the Mine Safety and Health Administration (MSHA) requiring levels of methane concentration to be maintained well below the 5 percent threshold, mine operators use large fans to provide a steady airflow across the mine face and ventilate the mine shaft. Typically, these ventilation systems release substantial quantities of methane in the fan exhaust.
- **Degasification Systems in Underground Mines.** When the volume of gas in underground mines is too high to be practically reduced to safe levels by standard ventilation techniques, degasification systems are employed. Degasification may take place before mining or may take the form of gob-wells or in-mine horizontal boreholes. Methane captured by degasification systems may be vented, flared, or recovered for energy. There are currently 25 mines in the United States employing degasification drainage systems, 15 of which are recovering and using the methane as an energy resource.
- **Surface Mines.** Because coal mined from the surface has formed at lower temperature and pressure than coal from underground mines, its methane content is lower. Further, because the coal is located near the surface, methane has had ample opportunity to migrate to the atmosphere before mining. Thus, while methane emissions from surface mines are heterogeneous in nature, they are systematically smaller than emissions from underground mines.
- **Post-Mining Emissions.** Methane that remains in coal pores after either underground or surface mining will desorb slowly as the coal is transported (typically by train) to the end user. Because coal that is consumed in large industrial or utility boilers is pulverized before combustion, methane remaining in the coal pores after transport will be released prior to combustion.
- **Methane Recovery for Energy.** In some cases (for example, in some mining degasification systems), methane is emitted from coal mines in sufficiently high volumes and concentrations to permit commercial recovery of the gas as either pipeline gas or fuel for electric power generation. Since coal mine methane recovered commercially is combusted, the quantities recovered are subtracted from estimates of total coal mine methane emissions.

Estimation Methods

Ventilation Systems in Underground Mines. Emissions from this source are segregated into two classes: emissions from "gassy" mines and emissions from "nongassy" mines.[115] Because methane concentrations and airflows in gassy mines are carefully monitored by the MSHA, a fairly reliable set of data can be derived for emissions from ventilation systems in gassy mines. However, MSHA data are voluminous, inconsistent in format, and difficult to compile, and they are available for only a subsample of years (1980, 1985, 1988, 1990, 1993, 1994, 1996, and 1997). Thus, the available data are used in conjunction with coal production data for those years to develop emissions factors per ton of coal mined on a basin-by-basin level.[116] Emissions factors for nonsample years are interpolated or extrapolated. The resulting emissions factors are then multiplied by production data to estimate emissions from this source (for detailed production data, see Table A5).

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[115] Gassy mines are defined as those underground coal mines with measured emissions from ventilation exhaust in excess of 100,000 cubic feet of methane per day.

[116] For purposes of this analysis, the Northern Appalachia basin includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; the Central Appalachia basin includes Eastern Kentucky, Virginia, Southern West Virginia, and Tennessee; the Warrior basin includes Alabama; the Illinois basin includes Illinois, Indiana, Western Kentucky, Iowa, and Oklahoma; and the Western basin includes Colorado, New Mexico, Utah, and Wyoming.

Table A5. Methane Emissions Factors for Gassy Coal Mines, 1990-1997
(Cubic Feet Per Day Per Short Ton of Coal Produced)

Basin	1990	1991	1992	1993	1994	1995	1996	1997
Northern Appalachia	1.01	1.09	1.17	1.24	0.79	0.80	0.81	0.81
Central Appalachia	1.45	1.42	1.39	1.35	1.17	1.17	1.17	1.17
Warrior	4.62	4.48	4.34	4.20	5.31	4.63	3.94	3.94
Illinois	0.44	0.46	0.48	0.49	0.47	0.49	0.50	0.50
Western	1.51	1.33	1.15	0.96	1.11	0.98	0.85	0.85

Sources: Coal Production numbers from Energy Information Administration Form 7-A, *Coal Production,* DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584, Ventilation data for 1990 and 1993 provided by G. Finfinger, U.S. Department of Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994,1996, and 1997 provided by Roger Fernandez, U.S. Environmental Protection Agency, Coalbed Methane Outreach Program.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.[117] Basin-level emissions factors for nongassy mines were established by dividing 2 percent of each basin's estimated emissions from nongassy mines for 1988 by that year's production levels. The resulting emissions factors are applied to annual production data.

Degasification Systems in Underground Mines. Degasification emissions are not monitored by any regulatory agency. Where degasification does occur, the method of disposition (e.g., venting, flaring, sale for energy) may not be tabulated. Estimated emissions from degasification systems during the period 1993 through 1996 are based data collected by the EPA's Office of Air and Radiation, Coalbed Methane Outreach Program, and published in *Identifying Opportunities for Methane Recovery at U.S. Coal Mines.*[118] For years prior to 1993, emissions from degasification systems are estimated by multiplying annual production in mines known to have degasification systems in place by a per-ton emissions factor. Because mine-by-mine production data are not yet available for the current year, 1997 emissions from degasification systems are scaled to increases in underground coal production.

Surface Mines. Emissions from U.S. surface mines have not been systematically measured. However, studies on surface coal mines in the United States, England, France, and Canada suggest a range of 0.3 to 2.0 cubic meters per metric ton of coal mined.[119] This report adopts the central value of that range and multiplies it by U.S. surface coal production.

Post-Mining Emissions. Like emissions from surface mines, post-mining emissions are not measured systematically. Thus, global average emissions factors must be applied. Post-mining emissions for coal mined from the surface are estimated to be very low, between 0.0 and 0.2 cubic meters per metric ton of coal mined. In contrast, post-mining emissions from underground coal are estimated to be more significant, between 0.9 and 4.0 cubic meters of methane per metric ton of coal mined.[120] The central values of these ranges are adopted and multiplied by annual production data for this report.

Methane Recovery for Energy. Methane recovery for energy is restricted to a small sample of mines that typically meter their gas sales. Thus, total methane recovery can be estimated from the volume and heat content of sales.

Data Sources

Ventilation Systems in Underground Mines. Coal mine ventilation data for the approximately 200 gassiest U.S. mines were drawn from a database prepared by the Department of Interior's Bureau of Mines for the years 1980, 1985, 1988, 1990, and 1993. Ventilation data for 1994, 1996, and 1997 were obtained from the EPA,

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[117] M.A. Trevits, G.L. Finfinger, and J.C. LaScola, "Evaluation of U.S. Coal Mine Emission," in Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium* (Littlejohn Co., 1991), p. 2.

[118] U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines,* EPA 430-R-97-020 (Washington, DC, September 1997), p. 5-19.

[119] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, web site www.iea.org/ipcc/invs6.htm.

[120] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, web site www.iea.org/ipcc/invs6.htm.

Atmospheric Pollution Prevention Division, Coalbed Methane Outreach Program. Coal production data are reported to the EIA on Form EIA-7A, "Coal Production Report." Basin-level emissions for nongassy mines in 1988 were calculated by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19–3-24.

Degasification Systems in Underground Mines. Data on drainage from degasification systems from 1993 through 1996 are from the EPA's Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA 430-R-97-020 (Washington, DC, September 1997). Emissions factors for this source are derived from estimates of 1988 emissions from degasification systems prepared by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19–3-24. Annual production figures are reported to the EIA on Form EIA-7A, "Coal Production Report."

Surface Mines. Emissions factors for surface mines are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Coal production data are reported to the EIA on Form EIA-7A, "Coal Production Report."

Post-Mining Emissions. Emissions factors for post-mining emissions are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Coal production data are reported to the EIA on Form EIA-7A, "Coal Production Report."

Methane Recovery for Energy. Methane recovery estimates for 1990 from EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Volumes of methane recovered during 1993 were obtained from U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines* (Washington, DC, September 1994), p. 6-6. Recovery volumes for 1996 were obtained from the EPA's Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA 430-R-97-020 (Washington, DC, September 1997). Recovery estimates for intervening years were extrapolated.

Stationary Combustion

Emissions Sources

The principal products of fuel combustion are carbon dioxide and water vapor. When fuel combustion is incomplete, methane may also be released. The volume of methane released varies according to the efficiency and temperature of the combustion process. Most stationary sources are large, comparatively efficient boilers, such as those found in the industrial and utility sectors, and thus have low levels of methane emissions. However, a significant amount of wood is consumed in residential woodstoves and fireplaces, which are typically inefficient combustion chambers. Wood combustion in these devices produces most of the U.S. methane emissions from stationary sources.

Estimation Methods

An emissions factor based on fuel type (for example, coal, wood, natural gas) and combustion technology (for example, utility boiler, industrial boiler, woodstove) is applied to consumption data for each fuel and technology type.

Data Sources

Emissions coefficients for stationary fuel were obtained from the EPA's Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Fuel consumption data were drawn from EIA's *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, September 1997) for 1980-1995; and *Monthly Energy Review*, DOE/EIA-0035(98/07) (Washington, DC, July 1998) for 1996-1997. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998).

Mobile Combustion

Emissions Sources

Methane emissions from mobile combustion are, like those from stationary combustion, the result of incomplete fuel combustion. In automobiles, methane emissions result when oxygen levels in the combustion chamber drop below levels sufficient for complete combustion. The effects of incomplete combustion in automobiles may be moderated somewhat by post-combustion emissions controls, such as catalytic converters. Methane emissions are also generated by fuel combustion in other modes of transport, including aircraft, ships, and locomotives. There is, however, some evidence that jet airplane engines may consume ambient methane during flight, reducing their net emissions.

Estimation Methods

Methane emissions from highway vehicles, such as automobiles, light-duty trucks, motorcycles, buses, and heavy-duty trucks, are estimated by applying emissions factors (per vehicle mile traveled) to vehicle use data. The emissions factors vary by vehicle type. Because of improving technology and more stringent environmental regulations, they have declined over time. For nonhighway sources, emissions coefficients in terms of volume of fuel consumed are applied directly to consumption data without year-to-year modifications.

Data Sources

Emissions factors for all vehicles are provided in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.65-1.75, web site www.iea.org/ipcc/invs6.htm. The EIA collects data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464(94) (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Emissions for intervening years were estimated by interpolating between the weighted average estimates of survey years. Vehicle miles traveled for nonhousehold vehicles (fleets, rental cars, etc.), motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics 1996* (Washington, DC, 1997), web site www.fhwa.dot.gov/ohim/1996/index.html.

Data on fuel consumption for ships, locomotives, farm equipment, and construction equipment are available in EIA's *Fuel Oil and Kerosene Sales 1997*, DOE/EIA-0535(97) (Washington, DC, September 1998). Fuel consumption data for jet and piston-powered aircraft are contained in EIA's *Petroleum Supply Annual 1997*, DOE/EIA-0340(97/1) (Washington, DC, May 1998). Data on fuel consumption by recreational boats are taken from S.C. Davis and S.G. Strang, *Transportation Energy Data Book*, Edition 17, ORNL-6919 (Oak Ridge, TN: Oak Ridge National Laboratory, Center for Transportation Analysis, August 1997), web site www.cta.ornl.gov/cta/data/tedb17/tedb17.html.

Landfill Methane Emissions

Emissions Sources

After organic wastes (e.g., food, paper, yard waste) are placed in landfills, they begin to decompose. Aerobic bacteria, consuming oxygen, convert organic material to carbon dioxide, heat, and water. When available oxygen is depleted, anaerobic bacteria, including methanogens, begin digesting the waste and producing methane. Methanogenic anaerobes are highly sensitive to temperature, pH, and moisture levels. Because U.S. sanitary landfills are essentially closed systems designed to minimize entry and exit of moisture, conditions within a landfill are largely a product of the composition of the waste it contains. Thus, methane is likely to be produced at different rates and volumes both across different landfills and within a single landfill.

The biogas produced in a landfill is typically between 35 and 50 percent methane. At these levels, methane is highly explosive. Often, landfill operators put methane control systems in place to prevent migration of high concentrations to buildings. Methane captured by control systems may be vented to the atmosphere or flared, but it is also a potentially valuable energy resource. Where landfills produce steady, large volumes of methane and landfill gas-to-energy prices are competitive with other energy alternatives, recovered gas may be used as an energy resource. In most cases, the gas is converted to electricity and used for on-site energy needs or sold to local utilities. In some cases, the gas is transported via pipeline to a local end user.

Estimation Methods

Data on methane emissions from landfills are limited to those landfills with methane recovery systems in place. For more than 100 U.S. landfills with gas recovery systems in place, Thorneloe et al. measured or estimated methane emissions at 2.1 million metric tons for 1992.[121] Methane emissions from landfills without gas recovery systems have not been measured, and even the number of landfills is subject to considerable uncertainty. Emissions from a given landfill are largely the product of the composition of the waste it contains and an array of site-specific factors. Waste composition data on a landfill-specific basis are nonexistent; however, national-level waste flow and waste composition data are available, and their reliability has improved over time. Thus, for this report, all waste not disposed

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[121] S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, "Estimate of Methane Emissions From U.S. Landfills," Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994), p. 1087.

of in a landfill with measured emissions is treated as if it has flowed to one very large national landfill.

To estimate methane emissions from all waste not disposed of in a landfill with measured emissions, waste volumes are subjected to a slightly modified version of the EMCON Methane Generation Model.[122] This model divides the waste into three categories: readily decomposable, moderately decomposable, and slowly decomposable, each with its own set of emissions characteristics. The EMCON model provides both a high methane yield scenario and a low methane yield scenario. For each category of decomposable waste, a time lag until methane generation begins is estimated, as well as a time constant during which the methane yield of the waste is realized. The methane yield represents the total amount of methane that a given amount of waste will produce over its lifetime. For example, under a low methane yield scenario, slowly decomposing waste will begin producing methane after a 5-year lag and will continue emitting over a 40-year period. Table A6 shows the EMCON methane generation model parameters.

Waste flows were estimated from 1940 through 1997. Waste in place in the Nation's landfills was assumed to represent the waste stream for all previous years plus the current year's additions. The landfills examined by Thorneloe et al. contained 9.2 percent of the waste estimated to be in place in the Nation's landfills during 1992. This report assumes that the share of waste in these landfills and the share in all other landfills remained constant over time. Thus, the EMCON model was applied to 90.8 percent of the waste generated each year.

To estimate emissions from those landfills with measured data for 1992 but no data for other years, the EMCON model was recalibrated to produce the 2.1 million metric tons of measured emissions in 1992. The recalibrated model, with methane yields almost twice as large as the original, was then applied to 9.2 percent of the waste stream for all years. These much higher yields are not unexpected, as gas recovery systems are most economically employed in high-emitting landfills.

Data Sources

Data on waste generated and landfilled for the period 1988 through 1997 (Table A7) were drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-1997). These data were not collected by *Biocycle* before 1988. Waste generated and landfilled for the period 1960 through 1987 was estimated from data produced by Franklin Associates. On behalf of the EPA's Office of Solid Waste and Emergency Response, Franklin Associates have estimated municipal solid waste (MSW) generated and landfilled for the years 1960 through 1996: Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States,*

Table A6. EMCON Methane Generation Model Parameters

Waste Category	Decomposable Portion (Percent by Dry Weight)	Methane Yield (Cubic Feet per Pound)	Lag Time (Years)	Time Constant
High Yield (Default)				
Readily Decomposable	4.0	4.50	0.2	3
Moderately Decomposable	45.0	3.55	1.5	10
Slowly Decomposable	5.2	0.50	5.0	20
Low Yield (Default)				
Readily Decomposable	4.0	2.75	0.3	4
Moderately Decomposable	45.0	1.95	2.0	20
Slowly Decomposable	5.2	0.29	5.0	40
High Yield (Modified)				
Readily Decomposable	4.0	8.82	0.0	3
Moderately Decomposable	45.0	6.96	2.0	10
Slowly Decomposable	5.2	0.98	5.0	20
Low Yield (Modified)				
Readily Decomposable	4.0	5.39	0.0	4
Moderately Decomposable	45.0	3.82	2.0	20
Slowly Decomposable	5.2	0.57	5.0	40

Source: D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environmental Change* (December 1992), pp. 311-328.

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[122] D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environment Change* (December 1992), pp. 311-328.

Table A7. Estimates of U.S. Waste Generated and Landfilled, 1990-1997
(Million Short Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Waste Generated	294	281	292	307	323	327	327	332
Waste Landfilled	226	213	210	218	216	206	203	202

Note: Totals may not equal sum of components due to independent rounding.
Source: "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-1997).

Worksheets, 1992 update, Prepared for the U.S. Environmental Protection Agency, Municipal Solid and Industrial Solid Waste Division (July 1992). See U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1996 Update*, EPA-530-S-96-001 (Washington DC, March 1997). In contrast to the *Biocycle* data, which include all waste going to landfills, including construction and demolition (C&D) waste and sludge, the Franklin data include only MSW going to landfills.

In order to account for categories of waste other than MSW going to landfills between 1960 and 1987, an average ratio of waste generation estimated by *Biocycle* and waste generation estimated by Franklin Associates for 1988 through 1997 was calculated. The annual average ratio during this period was 1.47 to 1. Thus, all Franklin estimates for 1960 through 1987 were multiplied by 1.47 to estimate overall waste generation and landfilling for those years. To further extend waste generation estimates back to 1940, a regression equation relating waste generation to GNP and population was developed.

Methane recovery data for 1992 were estimated from the measured recovery data provided by S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, "Estimate of Methane Emissions from U.S. Landfills," prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994). Methane recovery data for 1997 from Mike McGuigan, SCS Engineers, "GHG Emission Reductions from Landfill Gas Emissions," presented at the 21st Annual Landfill Gas Symposium (Austin, Texas, March 23-26, 1998). Recovery estimates for 1993 through 1996 were interpolated from the 1992 and 1997 data.

Domestic and Commercial Wastewater Treatment

Emissions Sources

Emissions of methane from the treatment of wastewater occur when liquid waste streams containing high concentrations of organic materials are treated anaerobically (in the absence of oxygen). Treatment processes used in the United States are anaerobic digestion, aerobic, and facultative (combining aerobic and anaerobic processes) stabilization lagoons, septic tanks, and cesspools.[123] Treatment of wastewater solids using anaerobic digestion is the most obvious potential source of methane emissions; however, emission of significant quantities of methane from this process requires that the digester gas be vented rather than recovered or flared. Anaerobic and facultative lagoons involve retention of wastewater in impoundments, where the organic materials in the wastewater undergo bacterial decomposition. The growth of algae, which absorb carbon dioxide and release oxygen as a result of photosynthesis, sustains aerobic conditions at least near the surface of the lagoon. Bacteria deplete oxygen at the bottom of the lagoon, producing conditions suitable for methanogenic bacteria. The extent of the resulting anaerobic zone and the associated methane generation depend on such factors as organic loadings and lagoon depth. In facultative lagoons, unlike anaerobic lagoons, a significant aerobic zone persists.

Nearly 75 percent of U.S. households are served by sewers that deliver domestic wastewater to central treatment plants. Septic tanks or cesspools treat domestic wastewater from most of the remaining households (24 percent).[124] Anaerobic digestion is frequently used to treat sludge solids at U.S. municipal wastewater treatment plants; however, anecdotal evidence suggests

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[123] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA 230-R-93-010 (Washington, DC, January 1994), p. 10-9.

[124] U.S. Census, 1980, 1990.

that neither recovery nor flaring of digester gas is common in the United States and that equipment for recovery and flaring of digester gas is poorly designed or maintained, allowing most of the methane produced to be released to the atmosphere.[125]

Estimation Methods

Insufficient information is available to develop separate estimates of methane emissions from each of the sources discussed above. Information on the type of treatment used by the thousands of municipal and industrial treatment facilities is simply not available. For instance, no reliable statistics were found for the use of anaerobic digestion at municipal treatment facilities. Knowledge regarding the emissions of methane from lagoons, septic systems, and cesspools is limited. Another difficulty is the overlap between municipal and industrial treatment systems. Many industrial concerns discharge wastewater, which may or may not have been treated, into municipal systems. Therefore, it is necessary to base the current estimate of methane emissions from wastewater treatment on the highly simplified approach recommended by the IPCC,[126] which assumes that each person in a developed nation contributes 0.05 kilogram of BOD_5 to domestic wastewater annually, and 15 percent of this wastewater is treated anaerobically, yielding 0.22 kilogram of methane per kilogram of BOD_5 in the wastewater.[127] It is assumed that recovery of methane at municipal wastewater treatment facilities is negligible.

Data Source

Estimate of the U.S. resident population on July 1 of each year were obtained from the U.S. Census Bureau.

Agricultural Sources

Enteric Fermentation in Domesticated Animals

Emissions Sources

The breakdown of carbohydrates in the digestive track of herbivores (including insects and humans) results in the production of methane.[128] The volume of methane produced from this process (enteric fermentation) is largest in those animals that possess a rumen, or forestomach, such as cattle, sheep, and goats. The forestomach allows these animals to digest large quantities of cellulose found in plant material. This digestion is accomplished by microorganisms in the rumen, some of which are methanogenic bacteria. These bacteria produce methane while removing hydrogen from the rumen. The majority (about 90 percent) of the methane produced by the methanogenic bacteria is released through normal animal respiration and eructation. The remainder is released as flatus.

Estimation Methods

The level of methane emissions from enteric fermentation in domesticated animals is a function of several variables, including quantity and quality of feed intake, the growth rate of the animals, their productivity (reproduction and/or lactation), and their mobility. To estimate emissions from enteric fermentation, the animals are divided into distinct, relatively homogeneous groups. For a representative animal in each group, feed intake, growth rate, activity levels, and productivity are estimated. An emissions factor per animal is developed from these variables. The factor is then multiplied by population data for the animal group to calculate an overall emissions estimate. The method for developing these factors differs somewhat for cattle as opposed to all other animals.

Cattle. Because emissions from cattle represent about 95 percent of U.S. emissions from enteric fermentation, they are given particular scrutiny. The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are then divided into replacement heifers 0-12 months old, replacement heifers 12-24 months old, and mature cows. Dairy cattle are further subdivided into regional populations in an effort to capture variations in diet and feed quality. Beef cattle are divided into six classes: replacements 0-12 months old, replacements 12-24 months old, mature cows, bulls, steers and heifers raised for slaughter under the weanling system, and steers and heifers raised for slaughter under the yearling system. These populations are then multiplied by emissions factors developed for each category of cattle based on their energy intake requirements.[129]

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[125] William Hahn, Science Applications International Corporation, personal communication, May 23, 1996.

[126] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 6.23, web site www.iea.org/ipcc/invs6.htm.

[127] Biological oxygen demand (BOD) represents the oxygen consumed by bacteria to decompose organic matter contained in a wastewater stream. It provides a measure of the organic loading of wastewater, which is the primary determinant of its potential to produce methane. BOD_5 is a standardized measurement of BOD that measures the oxygen consumed over a 5-day period.

[128] P.J. Crutzen, I. Aselmann, and W.S. Seiler, “Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans,” *Tellus*, Vol. 38B (1986), p. 272.

[129] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 5-3; and U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996,* Draft Report, (Washington, DC, March 1997), pp. 161-162.

Because characteristics critical in determining energy intake, and thus emissions rates, for cattle—such as growth rates and milk production—change annually, an effort is made to scale emissions factors to these changes. For dairy cattle, emission factors are scaled to average milk production per cow on a regional basis. For beef cattle, emissions rates are pegged to average slaughter weights for calves and adult cattle respectively (Table A8).

Other Animals. For sheep, pigs, goats, and horses, populations are not disaggregated below the species level. Emissions factors for each animal group are multiplied by their respective populations. Emissions factors are drawn from the work of Crutzen et al.[130]

Data Sources

Population and slaughter weight data for cattle and population data for sheep and swine were obtained from the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site www.mannlib.cornell.edu. Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1982, 1987, and 1992).

Solid Waste of Domesticated Animals

Emission Sources

When the solid waste of animals is allowed to decompose under anaerobic conditions, methane is produced. The volume of methane produced varies according to the amount of organic material susceptible to decomposition within the waste (volatile solids) and the manner in which the waste is managed. Liquid-based waste management systems, in addition to providing a suitable anaerobic environment, provide the moisture necessary for methanogenic bacterial cell production and acid stabilization.[131] Thus, they result in the most substantial methane emissions.

Estimation Methods

Methane emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, and the manner in which the waste is managed. The volume of waste produced is controlled by the animal's size, diet, and energy requirements. Typical animal sizes for beef cattle, swine, poultry, goats, sheep, and horses are drawn from a 1990 inventory of livestock emissions prepared by the EPA.[132] Animal sizes for beef cattle are adjusted annually on the basis of live slaughter weights as reported by the U.S. Department of Agriculture. Volatile solids produced per kilogram of animal weight, maximum methane-producing capacity of each animal's waste, and the share of waste managed in each management system are adopted from the work of Safley et al.[133] For all animals except dairy cattle, the share of waste managed in each management system is also drawn from Safley et al.

Methane conversion factors for dairy cattle are adopted on a State-by-State basis and are calculated from a weighted average of each State's manure management technique. Dairy cattle size and volatile solid production are drawn from the EPA.[134] Resulting emissions factors are applied to State population data acquired from the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch.

Table A8. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990-1997
(Pounds)

Animal Class	1990	1991	1992	1993	1994	1995	1996	1997
Cattle	1,134	1,136	1,163	1,169	1,161	1,189	1,183	1,169
Calves	260	281	346	376	388	384	372	341

Source: U.S. Department of Agriculture, Internet Site @gopher.usda.mannlib.cornell.edu.

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[130] P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), pp. 274-275.

[131] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 6-4.

[132] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 6-8.

[133] L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions From Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), p. 18.

[134] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1997), p. 164.

Data Sources

Population and slaughter weight data for cattle, and population data for sheep, poultry, and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site www.mannlib.cornell.edu. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens slaughtered annually by 0.1425, based on their 7-week life cycle as recommended by the USDA's Economic Research Service.[135] Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1982, 1987, and 1992).

Rice Cultivation

Emissions Sources

Methane is produced when organic material in flooded rice fields decomposes in the absence of oxygen (anaerobically). Between 60 and 90 percent of the methane generated is oxidized by bacteria in the soil, while an additional portion leaches into the groundwater. The majority of the methane that remains is transported through rice plants and is transpired into the atmosphere. A smaller amount of methane reaches the atmosphere by bubbling from the soil and by diffusing through the water column.

Estimation Methods

A range of daily emissions rates has been developed from studies of rice fields in California,[136] Louisiana,[137] and Texas.[138] The high and low ends of the range, 0.1065 and 0.5639 grams of methane per square meter of land cultivated, are applied to the growing season length and the harvested area for each State that produces rice. In States with a second ("ratoon") crop, the additional area harvested is incorporated into the estimates.

Data Source

Rice area harvested and length of growing season data were obtained from the USDA, National Agricultural Statistics Service, *Crop Production* (annual reports).

Burning of Crop Residues

Emissions Sources

Between 40 and 50 percent of dry matter in crop residue is carbon.[139] When crop residues are burned for fodder, land supplementation, or fuel, incomplete combustion produces methane emissions.

Estimation Methods

As reported by the EPA,[140] this report assumes that 3 percent of all crop residues are burned, with the exception of rice grown in California.[141] The share of rice crop residues in California estimated to be combusted declines in straight-line fashion from 99 percent in 1990 to 50 percent in 1996. The 50 percent estimate is held constant for 1997. These estimates of crop residues burned are in contrast to earlier estimates of 10 percent for all crops, adopted from default values provided by the IPCC. To derive methane emissions, the dry weight and carbon content of each crop were determined and then multiplied by estimated combustion efficiencies (Table A9).

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports); and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

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[135] Personal communication, May 1993.

[136] R. Sass, F. Fisher, S.Lewis, M. Jund, and F. Turner, "Methane Emissions From Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135.

[137] R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux From a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209.

[138] C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

[139] A. Strehler and W. Stutzle, "Biomass Residues," in D.O Hall and R.P. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), p. 85.

[140] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998), p. 93.

[141] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998), p. 93.

Table A9. Factors Used To Estimate Methane and Nitrous Oxide Emissions from Burning of Crop Residues

Crop Type	Ratio of Residue to Crop Volume	Dry Matter Content (Percent)	Carbon Content (Percent)	Nitrogen Content (Percent)
Barley	1.2	85.0	45.7	0.43
Beans	2.1	85.4	[c]45.0	[a]2.30
Corn	1.0	78.0	47.1	0.81
Oats	1.3	[b]90.1	[a]42.0	[a]0.84
Peas	1.5	[b]90.2	[c]45.0	[c]2.30
Peanuts	1.0	90.1	[c]42.3	[c]1.10
Potatoes	0.4	[c]86.7	42.3	1.10
Rice	1.4	85.0	41.4	0.67
Rye	1.6	[c]90.0	[c]48.5	[c]0.70
Sorghum	1.4	88.0	[a]34.0	[d]0.85
Soybeans	2.1	86.7	[a]44.0	[d]2.30
Sugar Beets	0.2	[c]90.0	40.7	2.28
Sugar Cane	1.2	37.2	47.0	0.19
Wheat	1.3	85.0	48.5	0.28

Sources: A. Strehler and W. Stutzle, "Biomass Residues," in D. Hall and R. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), except where indicated by: (a) C. Li, S. Frolking, and R. Harriss, "Modeling Carbon Biogeochemistry in Agricultural Soils," *Global Biogeochemical Cycles*, Vol. 8 (September 1994); (b) E. Darley, *Emission Factors from Burning Agricultural Wastes Collected in California*, Final Report, CAL/ARB Project 4-011 (Riverside, CA: University of California, 1977); (c) U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993*, EPA 230-R-94-014 (Washington, DC, September 1994); (d) G. Barnard, "Use of Agricultural Residues as Fuel," in J. Pasztor and L. Kristoferson (eds.), *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990).

Industrial Processes

Chemical Production

Emissions Sources

A wide variety of organic compounds (those containing carbon) are used as feedstocks in chemical production. High temperatures are often used to "crack" the molecular bonds of the compounds, with different temperatures producing specific chemicals. The process of cracking produces a number of chemical byproducts, including methane.

Estimation Methods

The IPCC has published emissions factors for methane emitted during the manufacture of ethylene, ethylene dichloride, styrene, methanol, and carbon black (Table A10). Production figures for the chemicals are multiplied by those emissions factors.

Data Source

Chemical production figures were obtained from the Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years).

Table A10. Methane Emissions Factors for Industrial Processes

(Grams of Methane Emitted
per Kilogram of Product Produced)

Industrial Product	Methane Emissions Factor
Coke	0.5
Sinter	0.5
Pig Iron	0.9
Carbon Black	11.0
Ethylene	1.0
Dichloroethylene	0.4
Styrene	4.0
Methanol	2.0

Source: Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, web site www.iea.org/ipcc/invs6.htm.

Iron and Steel Production

Emissions Sources

Coke, sinter, and pig iron are the principal material inputs for the production of iron and steel. Coke is produced by heating coal in the absence of oxygen. One of the gaseous byproducts of this process is methane. During the next step in the production process, coke, iron ore, and flux materials are combined to form sinter. The coke is burned to create heat, causing the sinter to agglomerate. During agglomeration, methane is released. Coke and iron are then added to flux materials in a blast furnace and reduced to iron, slag, and exhaust gases. Methane is one of the exhaust gases.

Estimation Methods

The IPCC has published emissions factors for methane emitted during the production of coke, sinter, and pig iron.[142] Production figures for iron and steel inputs are multiplied by those emissions factors.

Data Source

Coke, sinter, and pig iron production data are published annually by the American Iron and Steel Institute in its *Annual Statistical Report* (Washington, DC, various years).

Nitrous Oxide

Most anthropogenic nitrous oxide emissions in the United States can be attributed to energy and agricultural sources. In particular, motor vehicle fuel combustion accounts for approximately 55 percent of 1997 estimated emissions of nitrous oxide. Another 33 percent of emissions are attributable to nitrogen fertilizer use and animal manure management. It should be noted that the range of uncertainty associated with emissions from mobile combustion and fertilizer use is quite large. Emissions estimates in this report include: mobile source combustion from passenger cars, buses, motorcycles, trucks, and other minor sources; stationary source combustion from the commercial, residential, industrial, and electrical utility sectors; fertilizer application; burning of crop residues; livestock manure management; human sewage; waste combustion; and industrial production of adipic acid and nitric acid.

Energy Use

Mobile Combustion

Emissions Sources

Nitrous oxide emissions are produced as a byproduct of fuel combustion. During combustion, nitrous oxide (N_2O) is produced as a result of chemical interactions between nitrogen oxides (NO, NO_2 and NO_3)and other combustion products. Since nitrous oxide decomposes at high temperatures, most stationary combustion systems (such as electric power generation) emit little nitrous oxide. However, under some conditions, the catalytic converters fitted as pollution control devices on most U.S. vehicles will convert nitrogen oxides into nitrous oxide. The relevant conditions appear to be when the catalytic converter is just warming up, but before it reaches normal operating temperature, if the catalytic converter is not working properly, or if the catalyst is affected by excessive levels of sulfur in the gasoline.

Estimation Methods

In general, EIA estimates of nitrous oxide emissions for road vehicles are based on multiplying an emissions factor (grams of nitrous oxide per mile driven) by national-level vehicle miles traveled. Research indicates that emissions rates differ by vehicle type and by type of catalytic converter (associated with the vintage of the motor vehicle). Consequently, the EIA partitions national-level vehicle miles traveled by vehicle type (car, light-duty truck, bus, motorcycle, heavy-duty truck), and then again by motor vehicle vintage (model year).

For non-highway sources, an emissions factor in grams of nitrous oxide per unit of fuel consumed is applied to fuel consumption data. Since off-road vehicles rarely have catalytic converters (and vintage data scarce) no attempt is made to track vehicle vintages for the non-highway sources.

Data Sources

Emissions factors for motor vehicle nitrous oxide have been the subject of considerable discussion and new research over the past year. Last summer, the IPCC released its *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (Paris, France, 1997). This document included revised nitrous oxide emissions factors for motor vehicles that were four times higher those used in the previous reference manual and in the previous edition of this report. However, the EPA's Office of Mobile Sources, stimulated by the IPCC report, undertook an automotive testing program in the summer of 1998. The Office of Mobile Sources results were published in U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide from Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), and have been used in this report. These emissions factors are considerably lower than the emissions factors in the IPCC report but somewhat higher than emissions factors used in last year's EIA report and higher than the emissions factors suggested by the IPCC for use with European vehicles.

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[142] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.iea.org/ipcc/invs6.htm.

The EIA collects data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS)—Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464(94) (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Emissions for intervening years were estimated by interpolating between the weighted average estimates of survey years. Vehicle miles traveled for non-household vehicles (fleets, rental cars, etc.), motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics 1996* (Washington, DC, 1997), web site www.fhwa.dot.gov/ohim/1996/index.html.

Data on fuel consumption for ships, locomotives, farm equipment, and construction equipment are available in EIA's *Fuel Oil and Kerosene Sales 1997*, DOE/EIA-0535(97) (Washington, DC, September 1998). Fuel consumption data for jet and piston-powered aircraft are contained in EIA's *Petroleum Supply Annual 1997*, DOE/EIA-0340(97)/1 (Washington, DC, May 1998). Data on fuel consumption by recreational boats are taken from S.C. Davis and S.G. Strang, *Transportation Energy Data Book*, Edition 17, ORNL-6919 (Oak Ridge, TN: Oak Ridge National Laboratory, August 1997), web site www.cta.ornl.gov/cta/data/tedb17/tedb17.html.

Stationary Combustion

Emissions Sources

As with mobile sources, nitrous oxide emissions are produced as a byproduct of fuel combustion. The three fuels of primary importance burned by stationary sources are coal, fuel oil, and natural gas. Combustion systems powered by coal produce the most nitrous oxide, approximately 76 percent of annual emissions. As a sector, electric utilities consistently account for more than one-half of total emissions. Other important sources are commercial facilities, industrial facilities, and residences.

Estimation Methods

Nitrous oxide emissions from stationary combustion are estimated by multiplying fuel consumption figures for each fuel type and stationary source by emissions factors for each type of fuel. The emissions factors used in this report differ from those used in previous years; therefore, emissions estimates may also be different from those presented in last year's report. Emissions are estimated by applying emissions factors for coal, oil, and natural gas to EIA's consumption data for each fuel in the commercial, residential, industrial, and electric utility sectors.

Data Sources

Fuel consumption data are from the EIA's *State Energy Data Report* (EIA-0214) database. The emissions factors used in this report are those recommended by the IPCC as derived from studies of numerous conventional systems: G.G. De Soete, "Nitrous Oxide From Combustion and Industry: Chemistry, Emissions and Control," in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), pp. 287-337.

Agriculture

Nitrogen Fertilization of Agricultural Soils

Emissions Sources

Nitrous oxide is a waste product of certain classes of bacteria normally present in soil. When nitrogen (in the form of natural or artificial fertilizers) is added to natural or agricultural soils, the action of these bacteria is stimulated. However, the extent to which adding nitrogen stimulates nitrous oxide emissions is highly uncertain. The bacteria that emit nitrous oxide have natural competitors, which may be more or less successful in particular settings. In addition, conditions may be more or less propitious for bacterial action: the soil may be too moist or too dry, too compacted, too acid or alkaline, too warm or too cold. The form in which nitrogen is applied may be subject to faster or slower release to the waiting bacteria. Further, excess nitrogen will escape from the location of application through runoff and will be subject to decomposition in diverse natural environments. Thus, measured emissions from even large numbers of specific sites are exceptionally difficult to generalize into an estimate of national emissions.

The most recent estimation methods of the IPCC have been revised to take a more comprehensive view of nitrous oxide emissions from this source. It broadens consideration of the sources of nitrogen applied to soils and considers nitrous oxide emissions downstream from the site of emissions.

Estimation Methods

Following the most recent IPCC *Reference Manual*, this report estimates nitrogen applications to soils from three sources:

- Use of nitrogen fertilizers (computed directly from fertilizer data)
- Nitrogen in animal manure applied to agricultural soils (estimated from animal populations)
- Nitrogen in crop residues applied to agricultural soils (estimated from crop production statistics).

Only the first source (nitrogen fertilizers) was covered last year. Following the IPCC, we assume that 1.25 percent of the nitrogen applied is emitted to the atmosphere as nitrous oxide, while 30 percent of the nitrogen is assumed to escape into the environment. Some 2.5 percent of the nitrogen that escapes is ultimately converted into nitrous oxide in the form of emissions from streams and bodies of water. A further 10 percent of the nitrogen applied to soils is assumed to be released as gas in the form of nitrogen oxides and ammonia, and 1 percent of that nitrogen is assumed to be ultimately converted into nitrous oxide.[143]

Data Sources

Estimates of total U.S. fertilizer consumption were obtained from reports by the Tennessee Valley Authority Fertilizer Research Center for various years through 1994—J.T. Berry et al., *Commercial Fertilizers* (Muscle Shoals, AL: Tennessee Valley Authority, Fertilizer Research Center, Reports for 1986-1991 and 1993-1994)—and The Fertilizer Institute for 1995 through 1997. For nitrogen in animal manure, see the section on "Solid Waste of Domesticated Animals." For nitrogen in crop residues, see the section on "Crop Residue Burning" under methane or nitrous oxide.

Crop Residue Burning

Emissions Sources

Crop residues are commonly disposed of by incorporation into the soil, spreading over the soil surface to prevent erosion, as animal bedding, or through burning. Burning crop residues releases nitrous oxide into the atmosphere. The burning of crop residues occurs throughout the United States, although it is illegal in certain areas. There are no accurate estimates of the amount of crop residue burned in the United States.

Estimation Methods

As reported by the EPA, this report assumes that 3 percent of all crop residues are burned, with the exception of rice grown in California.[144] The share of rice crop residues in California estimated to be combusted declines in straight-line fashion from 99 percent in 1990 to 50 percent in 1996. The 50 percent estimate is held constant for 1997. These estimates of crop residues burned are in contrast to earlier estimates of 10 percent for all crops, adopted from default values provided by the IPCC. The amount of crop residue burned is discounted by an assumed combustion efficiency, multiplied by its dry matter content and nitrogen content, and then converted to nitrous oxide using a standard ratio of nitrous oxide to nitrogen content.

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports); and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Solid Waste of Domesticated Animals

Emissions Sources

Nitrous oxide is emitted as part of the denitrification of animal manure. The volume of nitrous oxide emissions is a function of the amount of manure produced, the nitrogen content of the manure, and the method for handling the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content that is emitted from anaerobic lagoon or other liquid systems.

Estimation Methods

Nitrous oxide emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, the nitrogen content of the waste, and the manner in which the waste is managed. Animal populations are divided into distinct, relatively homogeneous groups. The U.S. cattle population is separated into dairy and beef cattle. Emissions of nitrous oxide from poultry, sheep, pigs, goats, and horses are also estimated. For each group of animals, a per-head volatile solids production and an associated nitrogen content within the volatile solids are assigned. These values are multiplied by animal populations to derive total nitrogen excreted. For each animal group, excretions are distributed among the manure management systems used. The ratio of nitrous oxide production to nitrogen content for each management technique

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[143] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.53, web site www.iea.org/ipcc/invs6.htm.

[144] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998), p. 93.

is applied to provide an emissions estimate for each animal group, broken down by manure management system. The emissions are then summed to calculate an overall emissions estimate.

Data Sources

Population and slaughter weight data for cattle and population data for sheep, poultry, and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site www.mannlib.cornell.edu. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens slaughtered annually by 0.1425, based on their 7-week life cycle as recommended by the USDA's Economic Research Service.[145] Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1982, 1987, and 1992). Volatile solids content, nitrogen content of wastes by species, manure management systems, and nitrogen to nitrous oxide conversion rates were taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Vol. 3 (Paris, France, 1997), pp. 4.88-4.93, web site www.iea.org/ipcc/invs6.htm.

Waste Management

Waste Combustion

Emissions Sources

Like other stationary and mobile combustion processes, the burning of garbage and nonhazardous solid waste produces nitrous oxide emissions. There are 160 municipal waste combustion plants in the United States, with 114 plants generating energy. Emission levels are dependent on the composition of waste burned and combustion temperatures.[146] Very high temperatures reduce nitrous oxide emissions.

Estimation Methods

The total annual volume of municipal solid waste generated in the United States was multiplied by the share of waste incinerated. Total waste incinerated was then multiplied by a factor of 30 grams of nitrous oxide per metric ton of waste incinerated to calculate total nitrous oxide emissions from this source.

Data Sources

Waste generation data and share incinerated were drawn from *Biocycle* magazine, "The State of Garbage in America" (April 1997). The emissions factor was taken from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/ globalwarming/inventory/1998-inv.html.

Human Sewage in Wastewater

Emissions Sources

When human sewage is treated in wastewater systems, the nitrogen-based organic matter in the waste generates nitrous oxide through nitrification and denitrification. Under aerobic conditions, ammonia is converted to nitrate. As oxygen dissipates and an anaerobic environment governs, nitrate is converted to nitrous oxide.

Estimation Methods

Nitrous oxide emissions are estimated as a function of national population, per capita protein consumption, and the fraction of nitrogen in protein. The fraction of nitrogen in protein is assumed to be 16 percent, and 1 kilogram of nitrous oxide is assumed to be emitted per 100 kilograms of nitrogen in wastewater.

Data Sources

U.S. population data are from the Bureau of Census. Per-capita protein intake is from the Food and Agriculture Organization, *FAOSTAT Statistical Database.* Nitrogen content and nitrous oxide conversion factor are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Industrial Processes

Adipic Acid Production

Emissions Sources

Manufacture of adipic acid is one of the two principal sources of nitrous oxide from industrial processes.

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[145] Personal communication, May 1993.

[146] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998), p. 111.

Adipic acid is used primarily in the manufacture of nylon fibers and plastics in carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes. In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Creation of nitrous oxide is an intrinsic byproduct of this chemical reaction.

Estimation Methods

Emissions of nitrous oxide from production of adipic acid are calculated by multiplying adipic acid production figures by nitrous oxide emissions coefficients. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.[147] Currently, three plants control emissions by thermally decomposing the nitrous oxide, and 98 percent of the potential emissions from the production of adipic acid, subject to abatement controls, are eliminated by this technique.[148] In 1997, 85.1 percent of total estimated U.S. production of adipic acid was subject to abatement control measures.

Data Sources

Adipic acid production figures were obtained *Chemical and Engineering News*, annual report on the "Top 50 Industrial Chemicals" (April issue, various years). For 1997, U.S. total adipic acid production was estimated from information on adipic acid production and industry characteristics, obtained from the Dupont Company, as well as information reported on DuPont's Form EIA-1605, "Voluntary Reporting of Greenhouse Gases." Dupont's 1996 Form EIA-1605 submission contained data on nitrous oxide emissions for 1992 through 1995. The adipic acid emissions coefficient was taken from M. Thiemens and W. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

Nitric Acid Production

Emissions Sources

Nitric acid is a primary ingredient in fertilizers. The process for manufacturing this acid involves oxidizing ammonia (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

Estimation Methods

The IPCC guidelines indicate emissions factors of 2 to 9 grams of nitrous oxide per kilogram of nitric acid manufactured.[149] The emissions estimates presented in this report are calculated by multiplying the annual quantity of nitric acid produced by the midpoint (5.5 grams nitrous oxide per kilogram of product) of the emissions range. There is, however, a considerable degree of uncertainty associated with this estimate.

Data Sources

Nitric acid production figures were based on data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on fertilizer materials. See also web site www.census.gov/industry/mq28b974.txt. The nitric acid emissions coefficient was taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm.

Halocarbons and Other Gases

Emissions Sources

Halocarbons and other gases have hundreds of uses, but the bulk of emissions come from a few broad categories of use:

- As refrigerants or working fluids in air conditioning and refrigeration equipment
- As solvents in various industrial processes
- As blowing agents for making insulating foams
- As fugitive emissions from various industrial processes, including the manufacture of halocarbons.

The emissions profile differs for each emissions source. Refrigerants are used in a closed cycle inside cooling equipment, and they tend to leak out when the equipment is scrapped or serviced. Some portion of the refrigerants is captured and recycled or destroyed, rather than emitted, when equipment is serviced. Halocarbons in solvent applications are often recycled, but net consumption (after recycling) is probably a good indicator

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[147] M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

[148] Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

[149] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.18, web site www.iea.org/ipcc/invs6.htm.

of emissions. Halocarbons used as blowing agents can be characterized by the type of foam manufactured: halocarbons used to make “open cell” foam are released to the atmosphere immediately, while halocarbons used to make “closed cell” foam are trapped within the foam for the life of the foam, which can vary (depending on the use) from a few weeks to many years.

Estimation Methods

For the years 1990 through 1996, the EIA has relied primarily on estimates of halocarbon emissions presented in the EPA’s *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998). However, in the case of perfluoromethane and perfluoroethane, 1990-1997 emissions were estimated on the basis of annual U.S. aluminum production and emissions factors of 0.6 kilogram of CF_4 and 0.06 kilogram of C_2F_6 per metric ton of aluminum. With the exception of these two PFCs, the preliminary 1997 emissions estimates were derived primarily by extrapolating the trends shown in the EPA estimates.

The new estimates presented this year differ from past estimates, due to differences between the methodologies and data sources used in the new EPA report and those used by the EIA and the EPA in the past. For example, whereas past EPA and EIA estimates assumed that HFC-23 emissions were equal to 2 to 4 percent of HCFC-22 production, EPA’s new HFC-23 emission estimates were based on measurements of feed components at individual HCFC-22 manufacturing plants, as well as measurements of HFC-23 concentrations in the process stream.[150] For HFCs, PFCs, and sulfur hexafluoride, the total new emissions estimates (expressed on a GWP-weighted basis) range from 12 percent to 21 percent less than the prior estimates for the 1990-1995 period.

Data Sources

EPA estimates of emissions of halocarbons and other gases are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Information on halocarbon production, consumption, and sales is spotty. Information on production and sales of some compounds, up to 1994, is provided in U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1994*, USITC Publication 2933 (Washington, DC, November 1995). The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) provides information on “world” and “northern hemisphere” production, sales, and emissions of certain halocarbons, as well as a breakdown of sales by anticipated end use: Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1995* (Washington, DC, January 1997). The end-use share data can be used to (crudely) estimate U.S. consumption for particular types of end uses. Large industrial emitters of certain halocarbons are required to report emissions, destruction, and recycling of these compounds. This information is published in U.S. Environmental Protection Agency, *1996 Toxics Release Inventory: Public Data Release-Ten Years of Right-to-Know* (Washington, DC, May 1998).

Emissions factors for perfluoroethane and perfluoromethane can be found in U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gases Emissions and Sinks: 1990-1993*, EPA-230-R-94-014 (Washington, DC, September 1994), p. 38.

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[150] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*, Draft Report (Washington, DC, March 1998), pp. 66-67.

Appendix B
Carbon Coefficients Used in This Report

Overview

The first edition of *Emissions of Greenhouse Gases in the United States*, published in September 1993, applied emissions coefficients developed by Marland and Pippin[151] that had been adopted by the Intergovernmental Panel on Climate Change.[152] Those coefficients, developed for broad international use, covered only the six petroleum product categories in the International Energy Agency's taxonomy. The Energy Information Administration (EIA) collects data on more than 20 petroleum products, and U.S. petroleum products often differ in composition from those consumed abroad. Thus, EIA needed coefficients for the specific products reported in U.S. energy statistics. Further, the emissions coefficients developed by Marland and Pippin were based on a very limited set of fuel samples.

In 1994, the EIA developed more specific and accurate emissions coefficients for estimating carbon released from the combustion of fossil fuels in the United States. The EIA developed emissions coefficients for coal by rank (anthracite, bituminous, subbituminous, and lignite) and State of production, using 5,426 coal samples from the EIA coal analysis file. An emissions coefficient for natural gas was generated, based on 6,743 gas samples in a Gas Research Institute database. Emissions coefficients for the petroleum products captured in EIA energy statistics were derived, based on their density, heat content, and carbon share. These variables were estimated on the basis of the underlying chemical composition of the fuels and, where available, ultimate analyses of product samples.[153]

In all but a few cases, the revised emissions coefficients differed from those developed by Marland and Pippin by less than 5 percent. The magnitude of potential variation in emissions coefficients for fossil fuels is constrained by the limits imposed by the chemical properties of the hydrocarbon compounds that define the fuels.[154] Although the marginal improvements in accuracy for the emissions coefficients were not large, a number of important insights were gained with regard to fuel composition trends and their effects on emissions coefficients.

The composition of marketed petroleum products varies over time because of changes in exploration, recovery, and refining technology, economic changes (e.g., changes in the price of oil), and regulatory changes (e.g., requirements for reformulated gasoline in the Clean Air Act Amendments of 1990). Four petroleum products prone to changes in their composition that have important effects on carbon emissions—either because emissions per unit may change substantially or because great volumes are consumed in the United States—are motor gasoline, jet fuel, crude oil, and liquefied petroleum gases (LPG). Thus, EIA has developed annualized emissions coefficients for these fuels in an effort to capture changes in composition (Table B1).

The most important changes have occurred in the emissions coefficient for motor gasoline. Motor gasoline consumption accounts for about 20 percent of all U.S. greenhouse gas emissions. Between 1986 and 1995, small increases in the density of gasoline led to a slowly escalating emissions coefficient. In 1995, a requirement for reformulated gasoline in nonattainment areas implemented under the Clean Air Act Amendments changed the composition of gasoline consumed in the United States. During 1995, 25 percent of all gasoline consumed was reformulated, rising to 32 percent in 1997. Because the additives contained in reformulated gasoline have much lower carbon shares than typical gasoline, the national average emissions coefficient for motor gasoline has reversed the previous

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[151] G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol.14 (1990), pp. 319-336.

[152] Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gas Emissions and Sinks* (1991), p. 2-18.

[153] An ultimate analysis provides an exact breakdown of the elements present in a compound or mixture.

[154] For a more detailed discussion of fossil fuel chemistry and emissions coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92, web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.

Table B1. Carbon Emissions Coefficients at Full Combustion, 1987-1997
(Million Metric Tons of Carbon per Quadrillion Btu)

Fuel	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Petroleum											
Motor Gasoline	19.38	19.39	19.41	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35
LPG	17.04	17.03	17.06	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99
Jet Fuel	19.42	19.42	19.41	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Petrochemical Feed	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Aviation Gas	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Waxes and Miscellaneous	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Industrial Sector "Other"[a]	17.61	17.68	18.00	17.78	18.14	17.75	16.59	16.68	15.69	16.32	16.77
Coal											
Residential/Commercial	25.90	25.87	25.94	25.92	26.00	26.13	25.97	25.95	26.00	25.92	25.92
Industrial Coking	25.38	25.40	25.40	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.55
Other Industrial	25.53	25.53	25.56	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.61
Electric Utility	25.64	25.67	25.67	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.74
Flare Gas	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Natural Gas	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Crude Oil	20.13	20.16	20.13	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24

[a] Composite coefficient based on final calculations, accounting for fraction not combusted and deductions for nonfuel use, using unpublished disaggregated energy data.

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997), pp. 99-104, and estimates presented in this report.

decade's trend and declined by about 0.5 percent over the past 3 years.

Jet fuel consumption is responsible for more than 4 percent of U.S. carbon dioxide emissions. Like motor gasoline, jet fuel consumed in the United States has undergone a dramatic change in composition over the past decade. Until 1993, two types of jet fuel were widely used in the United States. Kerosene-based jet fuel was generally used in the commercial airline industry and naphtha-based jet fuels were used primarily by the U.S. Department of Defense. The emissions coefficient for naphtha-based jet fuels was about 3 percent higher than that for kerosene-based jet fuel. In 1989, 13 percent of all jet fuel consumed was naphtha-based. By 1996, that figure had fallen to 0.3 percent, and in 1997 total naphtha-based jet fuel consumption was negligible. Thus, the emissions coefficient for jet fuel, weighted by consumption of each fuel type, fell steadily between 1988 and 1996 and has now stabilized at the level of kerosene-based jet fuel.

The emissions coefficient for LPG is a weighted average of the emissions coefficient for four paraffinic hydrocarbons: ethane, propane, isobutane, and *n*-butane. The emissions coefficient for this source varies according to the proportion of each compound consumed and whether the compounds are used as petrochemical feedstock or for fuel. Last year, for the first time, EIA began publishing separate emissions coefficients for LPG fuel use and LPG nonfuel use. LPG emissions coefficients for 1997 are unchanged from 1996.

Crude oil consumption in the United States is a very small portion of carbon emissions, because nearly all crude is refined into finished petroleum products. However, crude oil does represent a much larger portion of consumption in the energy statistics of other nations and can offer a "quick and dirty" mass balance approach to estimating trends in national emissions. The EIA has developed a regression equation reflecting the relationship between the density, sulfur content, and carbon content of crude oil. From these data a crude oil emissions coefficient can be calculated. The density of crude oil entering U.S. refineries has risen gradually over the past decade. Thus, each barrel of oil now contains a greater mass of oil and a greater weight of carbon. Because the presumed heat content of a barrel of crude oil has not changed, the emissions coefficient continues to rise slowly.

Motor Gasoline

As with all petroleum products, the emissions coefficient for motor gasoline is a function of its density and carbon content. This relationship is particularly clear in the case of motor gasoline, because the share of impurities found in the fuel must be kept low to maintain the operating condition of modern automobile engines and limit the environmental impact of vehicle use. Motor gasoline density varies between summer and winter grades and from low octane to high octane. The variation takes into account the differing performance requirements of gasoline associated with temperature changes. Partly as a result of the phaseout of leaded gasoline, the density of gasoline increased slowly and steadily across all octane grades and in all seasons from 1987 through 1994.[155] In order to maintain the "anti-knock" quality and octane ratings of motor gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline was increased. Aromatic hydrocarbons take the form of C_nH_{2n-6}, a lower ratio of hydrogen to carbon than in the other hydrocarbons typically found in gasoline. Because carbon is much heavier than hydrogen, the lower ratio results in greater fuel density and higher shares of carbon. As a result, the emissions coefficient for motor gasoline rose slowly from 19.39 million metric tons carbon per quadrillion Btu in 1988 to 19.45 million metric tons carbon per quadrillion Btu in 1994. Table B2 shows the increasing densities and emissions coefficients for that time period.

Reformulated gasoline was consumed in large volumes (about 25 percent of overall gasoline consumption) for the first time during 1995. The density of reformulated gasoline is about 1 percent less than that of standard gasoline, and the much lower carbon contents of the principal additives to reformulated gasoline (Table B3) reduce the overall share of carbon in reformulated fuel. Thus, taking into account the 25 percent of fuel consumed with a lower emissions profile, the emissions coefficient for motor gasoline dropped from 19.45 million metric tons per quadrillion Btu in 1994 to 19.38 million metric tons per quadrillion Btu in 1995. By 1997, reformulated gasoline accounted for 32 percent of total gasoline consumption, and the overall emissions coefficient declined to 19.35 million metric tons carbon per quadrillion Btu.

To derive an overall emissions coefficient for gasoline, individual coefficients for standard motor gasoline consumed in the winter and summer months were developed. The coefficients were based on the densities of product samples collected by the National Institute on

Table B2. Changes in Motor Gasoline Density, 1988-1997
(Degrees API)

Fuel Grade	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Winter Grade										
Low Octane	62.2	62.0	62.0	61.8	61.4	61.0	60.1	59.8	60.6	P61.0
Mid Octane	NA	59.9	60.8	60.4	60.2	59.9	59.4	59.1	59.9	P60.4
High Octane	59.6	58.8	59.0	59.3	59.0	58.7	58.5	58.0	58.5	P59.0
Summer Grade										
Low Octane	58.9	58.2	58.2	58.0	57.4	56.1	55.7	56.1	56.9	57.1
Mid Octane	NA	57.1	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6
High Octane	56.8	55.3	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4
Average Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**19.39**	**19.41**	**19.41**	**19.41**	**19.42**	**19.43**	**19.45**	**[a]19.38**	**[a]19.36**	**[a]P19.35**

[a]Emissions coefficient weighted for reformulated gasoline, which has a lower density than standard gasoline.

P = preliminary data.

Sources: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline, Winter* (1984-1997); and M. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Vol. 2, Appendices A-S, ANL/ESD/TM-22 (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6. Properties of reformulated fuels from California Air Resources Board.

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[155] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline, Winter* (1984-1994).

Table B3. Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)	Emissions Factor (Million Metric Tons per Quadrillion Btu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Sources: California Air Resources Board, and estimates developed for this report.

Petroleum and Energy Research (NIPER), used in conjunction with a carbon share of 86.6 percent as estimated by Mark DeLuchi.[156] Emissions coefficients for reformulated fuels consumed during the summer and winter were calculated by the following procedure. First, the carbon share of each additive used in reformulated gasoline was calculated from its chemical formula and combined with the additive's density and energy content, as provided by the California Air Resources Board, to produce individual coefficients for each fuel additive. Next, the reformulated fuel was separated into its standard fuel components and its additive portions, based on fuel samples examined by NIPER.[157] The additive portions were defined as the net increase in MTBE, ETBE, or TAME as compared with the additives in standard fuel, because small amounts of these compounds are present in standard gasoline. The emissions coefficients for standard gasoline and for each of the additives were then weighted by their proportion in reformulated fuel to arrive at a coefficient for reformulated fuel in each season.

After independent coefficients were developed for both standard and reformulated fuel, each season's coefficients were combined by weighting according to the ratio of standard to reformulated consumption. The combined summer and winter coefficients were then weighted on the basis of seasonal consumption, with just over half occurring in summer, to derive an overall emissions coefficient for motor gasoline.

Jet Fuel

The EIA collects data on two classes of jet fuel: naphtha-based and kerosene-based. In 1989, the share of U.S. jet fuel consumption attributed to naphtha-based fuel was 13 percent, and the remainder was kerosene-based jet fuel. The emissions coefficients for these two fuel classes differed, with an emissions coefficient of 19.95 million metric tons carbon per quadrillion Btu for naphtha-based fuel and 19.33 million metric tons carbon per quadrillion Btu for kerosene-based fuel. A jet fuel coefficient was developed by weighting the emissions coefficient for each class of fuel on the basis of its consumption. By 1993 the share of naphtha-based jet fuel had dropped to 7.2 percent, most of which could be credited to consumption in military aircraft. The U.S. Department of Defense then began a conversion from naphtha-based JP-4 jet fuel to kerosene-based JP-8 jet fuel, fearing that the increased demand for reformulated motor gasoline could inhibit refinery production of naphtha-based jet fuel. By 1995 naphtha-based jet fuel represented less than 1 percent of consumption, and today only negligible amounts are used.[158] Thus, the 1997 emissions coefficient for jet fuel is simply that of kerosene-based jet fuel and can be expected to remain nearly stable for the foreseeable future.

The emissions coefficient for kerosene-based jet fuel was developed by using data from 39 samples of Jet A collected and analyzed by Boeing.[159] The average density of the samples was 44.5 degrees API gravity, and the average carbon share was 85.8 percent. The resulting emissions coefficient is 19.33 million metric tons per quadrillion Btu (Table B4).

Crude Oil

Although crude oil composition is highly heterogeneous, the share of carbon in a fixed amount of crude oil (e.g., a gallon or barrel) varies somewhat systematically with such commonly available identifying characteristics as density and sulfur content. Because

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[156] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer 1995* and *Motor Gasoline, Winter 1994-1995*; and M. DeLuchi, *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*, Vol. 2, Appendices A-S, ANL/ESD/TM-22 (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6.

[157] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer 1995* and *Motor Gasoline, Winter 1994-1995.*

[158] Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 17.

[159] O.J. Hadaller and A.M. Momenthy, *The Characteristics of Future Fuels*, Part 1, "Conventional Jet Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50.

the economic value of a barrel of crude oil is largely a product of the oil's density and sulfur content, these values are regularly recorded. Further, the EIA maintains detailed data on the average density and sulfur content of crude oil entering U.S. refineries.[160] Thus, the annual emissions coefficient for crude oil is pegged to these two variables.

Ultimate analyses of 182 crude oil samples were used to derive a relationship between crude oil density, sulfur content, and the percentage of carbon in crude oil. The sulfur content and density of the samples was regressed against their carbon content to produce the following equation, which is used to estimate the carbon content of crude oil:

$$\text{Percent Carbon} = 76.99 + (10.19 \times \text{Specific Gravity}) + (-0.76 \times \text{Sulfur Content}) \quad .$$

Annualized emissions coefficients are developed by inserting the average density and sulfur content for crude oil entering U.S. refineries for each year from 1987 through 1997 to provide the share of carbon in an average barrel of oil during each year. After the share of carbon is derived, it is used in conjunction with fuel density to estimate the total mass of carbon in a barrel of crude oil. An emissions coefficient per unit of energy is then calculated from EIA's standard energy content for crude oil of 5.8 million Btu per barrel.

The 1997 emissions coefficient for crude oil is 20.24 million metric tons carbon per quadrillion Btu, a slight decrease from the 1996 value. The change can be traced to a relatively large jump in the sulfur content of crude oil, which rose from 1.15 percent to 1.25 percent, its highest level in at least two decades. The increase in sulfur content more than offset a very small increase in the density of crude oil and lowered the share of carbon in crude oil entering U.S. refineries form 84.98 percent to 84.91 percent (Table B5).

Table B4. Consumption-Weighted Emissions Coefficients for Jet Fuel, 1990-1997
(Million Metric Tons Carbon)

Data Element	1990	1991	1992	1993	1994	1995	1996	1997
Share of Naphtha-Based Jet Fuel (Percent) . . .	11.4	12.0	9.4	7.2	2.9	1.0	*	*
Share of Kerosene-Based Jet Fuel (Percent) . .	88.6	88.0	90.6	92.9	97.1	99.0	100.0	100.0
Weighted Emissions Coefficient	**19.40**	**19.40**	**19.39**	**19.37**	**19.35**	**19.34**	**19.33**	**19.33**

Sources: Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years). O.J. Hadaller and A.M. Momenthy, *The Characteristics of Future Fuels*, Part 1, "Conventional Jet Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50. C.R. Martel and L.C. Angello, "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," in *Current Research in Petroleum Fuels*, Vol. I (New York, NY: MSS Information Corporation, 1977), p. 116.

Table B5. U.S. Crude Oil Characteristics, 1990-1997

Characteristic	1990	1991	1992	1993	1994	1995	1996	1997
Density (API Gravity)	31.86	31.64	31.32	31.30	31.39	31.30	31.13	31.07
Density (Specific Gravity)	0.8662	0.8674	0.8691	0.8692	0.8686	0.8692	0.8701	0.8704
Sulfur Content (Percent)	1.10	1.13	1.16	1.15	1.14	1.13	1.15	1.25
Carbon Share (Percent)	84.98	84.97	84.96	84.97	84.97	84.99	84.99	84.91
Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**20.16**	**20.18**	**20.22**	**20.23**	**20.21**	**20.23**	**20.25**	**20.24**

Note: Emissions coefficients assume 100 percent combustion.

Sources: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), p. 91.

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[160] Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 16.

Liquefied Petroleum Gases

The EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and *n*-butane. Because each of these hydrocarbons is a pure paraffinic compound, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (one). Thus, for example, the carbon share of ethane, C_2H_6, which has an atomic weight of 30, is 80 percent. The densities of these compounds are also well known, allowing emissions coefficients to be calculated easily. The EIA collects data on consumption of each compound and then reports them as LPG in the *Petroleum Supply Annual*.[161] By weighting each compound's individual emissions coefficient by its share of energy consumed, an overall emissions coefficient for LPG is derived.

LPG may be used as fuel or as a petrochemical feedstock. About three-quarters of the carbon in petrochemical feedstocks will be sequestered. Further, if the mix of paraffinic hydrocarbons used for petrochemical feedstock differs substantially from those used for fuel, using a single emissions coefficient for LPG will bias estimates of emissions. More than 95 percent of all ethane and just under 85 percent of butane consumed goes to nonfuel uses. In contrast, nearly all LPG used as fuel is propane. Thus, the emissions coefficient for LPG used as fuel is 17.20 million metric tons carbon per quadrillion Btu, which is the emissions coefficient for propane (Table B6). On the other hand, the carbon emissions coefficient for LPG for nonfuel use is pulled down to 16.86 million metric tons carbon per quadrillion Btu by the large presence of the lighter ethane and its emissions factor of 16.25 million metric tons per quadrillion Btu.

Table B6. Emissions Coefficients for Liquefied Petroleum Gases, 1988-1997
(Percent)

Fuel	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Carbon Content of LPG Consumption for Fuel Use (Million Metric Tons)										
Ethane	0.75	0.86	0.47	0.30	0.45	0.28	0.39	0.40	0.44	0.44
Propane	15.66	15.08	13.67	13.53	14.48	14.78	14.79	14.82	15.41	16.60
Butane	2.61	2.35	1.33	0.87	1.29	1.08	1.27	0.83	0.90	0.76
Total	19.03	18.30	15.46	14.70	16.22	16.14	16.45	16.06	16.74	17.81
LPG Consumption for Fuel Use (Quadrillion Btu)										
Ethane	0.05	0.05	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.03
Propane	0.91	0.88	0.79	0.79	0.84	0.86	0.86	0.86	0.90	0.97
Butane	0.15	0.13	0.08	0.05	0.07	0.06	0.07	0.05	0.05	0.04
Total	1.10	1.06	0.90	0.85	0.94	0.94	0.96	0.93	0.97	1.04
Weighted Average Fuel Use Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**17.23**	**17.22**	**17.21**	**17.21**	**17.21**	**17.22**	**17.22**	**17.20**	**17.20**	**17.20**
Carbon Content of LPG Consumption for Nonfuel Use (Million Metric Tons)										
Ethane	8.78	7.63	8.86	10.11	10.07	10.57	10.54	11.00	12.10	11.93
Propane	6.62	8.77	9.08	10.11	10.45	9.45	11.21	11.56	12.02	11.25
Butane	3.36	3.62	2.27	2.98	2.90	2.68	4.35	4.22	4.52	4.49
Total	18.77	20.02	20.22	23.20	23.42	22.70	26.10	26.78	28.64	27.66
LPG Consumption for Nonfuel Use (Quadrillion Btu)										
Ethane	0.54	0.47	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.73
Propane	0.38	0.51	0.53	0.59	0.61	0.55	0.65	0.67	0.70	0.65
Butane	0.19	0.20	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.25
Total	1.12	1.18	1.20	1.38	1.39	1.35	1.55	1.59	1.70	1.64
Weighted Average Nonfuel Use Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**16.83**	**16.91**	**16.83**	**16.84**	**16.84**	**16.80**	**16.88**	**16.87**	**16.86**	**16.86**

Note: Emissions coefficients assume 100 percent combustion.

Sources: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gases* (Washington, DC, various years).

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[161] Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 2.

Appendix C
Uncertainty in Emissions Estimates

Overview

The Energy Information Administration (EIA) has prepared subjective estimates of the reliability of the different methods used to estimate emissions in this report. The estimates fall into several categories:

- Uncertainty associated with underlying activity data and uncertainty associated with emissions factors
- Random errors and bias errors
- Potential for upward and downward bias errors
- Reliability of emissions estimates by source.

The distribution of uncertainty estimates is summarized in Table C1, which excludes estimates for emissions and sequestration from land uses changes and forestry. Summarizing all the uncertainties, it is possible that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 12 percent from the estimates in this report. Much of the uncertainty in national emissions comes from nitrous oxide emissions, for which estimates are accurate only to within 100 percent and which accounts for about half the uncertainty in the national estimate. Excluding this source, the uncertainty of the total estimate is less than 10 percent.

The bulk of the potential uncertainty in the overall national estimate takes the form of bias errors, which are likely to persist from one year to the next and, thus, to have relatively little influence on trends, rather than random errors, which would increase the difficulty of determining whether or not a trend exists. This is because estimates of energy-related carbon dioxide are probably accurate to well within 10 percent of estimated emissions, and energy-related carbon dioxide accounts for 82 percent of national emissions of greenhouse gases. There are much larger uncertainties for methane and, particularly, for nitrous oxide emissions, but the present evidence suggests that emissions from these sources accounts for only a small portion of total emissions.

The uncertainties in the estimates presented in this report come from the following sources:

- **Evolving definitions.** In general, this report attempts to measure "anthropogenic" (human-caused) emissions and sequestration of greenhouse gases in the United States, excluding emissions of carbon of biological origin. Although in most cases it is obvious whether emissions from a particular source fall within this definition, there are a number of ambiguous cases, and the range of accepted definitions has shifted over time. Since the first edition of this report, sulfur hexafluoride has been added to the generally accepted definition of "greenhouse gases." And it has recently been decided that emissions from bunker fuel are excluded from the definition of "U.S. emissions." Definitional changes tend to raise or lower emissions estimates systematically.
- **Emissions sources excluded from the report.** An estimate that excludes some sources will be biased downward by the amount of the excluded source. Of course, if the existence or magnitude of the excluded emissions were known, they would be included. But it is probable that there are still sources that are excluded from this estimate.
- **Incorrect models of emissions processes.** An estimate based on a belief that emissions are caused by (or can be estimated from) a particular activity or process can produce large, systematically biased errors if the emissions are actually caused by some other process. The incorrect method can produce estimates that are considerably higher or lower than actual emissions and have different time-series properties.
- **Emissions factor errors.** Errors in emissions factor can have diverse causes, the most common of which are definitional errors, sampling errors, and measurement errors. These errors can be either random or systematic.
- **Activity data errors.** Activity data are also subject to definitional errors, frame errors, sampling errors, and measurement errors, which can be either random or systematic.
- **Computational errors.** Computational errors can exist in the estimation of emissions factors by the EIA, in the calculation of emissions by the EIA, or

Table C1. Reliability of Emissions Estimates in This Report

Greenhouse Gas and Source of Emissions	Share of Source in U.S. Emissions Total (Percent)	Estimated Errors in Activity Data (Percent of Total for Source)			Estimated Errors in Emissions Factors (Percent of Total for Source)			Weighted Uncertainty (Percent of Total Emissions)	
		Bias			Bias				
		Low	High	Random	Low	High	Random	Low	High
Carbon Dioxide									
Petroleum	35.0	2.1	2.4	0.5	1.7	1.7	0.5	1.0	1.1
Coal	29.8	0.6	4.3	0.6	1.0	1.0	0.5	0.4	1.3
Natural Gas	17.8	0.5	2.9	0.5	0.0	0.0	0.4	0.1	0.5
Other	1.2	0.0	9.1	6.0	11.8	11.8	3.2	0.2	0.2
Missing Sources	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.4
Total	83.8	1.2	3.8	0.6	1.2	1.2	0.5	1.7	3.5
Methane									
Energy-Related	3.2	13.1	13.9	4.9	20.8	25.0	4.5	0.8	0.9
Agricultural	2.8	3.1	5.0	3.0	36.3	36.3	10.5	1.0	1.1
Industrial and Waste	3.4	9.8	28.5	5.1	48.3	13.2	9.6	1.6	1.1
Missing Sources	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	9.3	8.9	20.6	4.4	35.3	24.1	8.1	3.5	3.1
Nitrous Oxide									
Energy-Related	1.2	0.5	2.9	0.5	55.0	200.0	10.0	0.7	2.5
Agricultural	3.0	4.0	5.0	4.3	90.0	100.0	10.0	2.7	3.1
Industrial and Waste	0.5	2.8	5.0	3.3	55.0	200.0	10.0	0.2	0.7
Missing Sources	0.0	0.0	15.0	0.0	0.0	0.0	0.0	0.0	2.5
Total	4.8	3.0	19.4	3.2	77.2	136.5	10.0	5.2	6.6
Other Gases									
HFCs, PFCs, SF_6	2.1	4.5	2.2	0.9	14.6	16.3	2.6	0.5	0.6
Missing Sources	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.2
Total	2.1	4.5	12.2	0.9	14.6	16.3	2.6	0.5	0.6
Total: All Sources	**100.0**	**2.1**	**6.3**	**1.1**	**8.3**	**10.1**	**1.7**	**11.9**	**12.1**

Notes: The “low” and “high” bias errors provide a subjective estimate of the largest bias error lower or higher than the current point estimate that would be consistent with current understanding of the nature of the activity or emissions mechanism. Each value is calculated as the weighted average of the uncertainties associated with a group of sources in each category. It is calculated as a percentage of the point estimate of emissions from that source. “Random error” is a subjective estimate of the largest random error that is consistent with current understanding of the nature of the activity or emissions estimate. “Weighted uncertainty” is calculated as the square root of the sum of the squared activity factor and emissions factor errors and then multiplied by the point estimate of the share of total emissions for the source. It is calculated as a percentage of the point estimate of total 1997 U.S. emissions.

Source: Estimates presented in this Appendix.

in the computation of the underlying activity data by the source organization. Although any single computational error will usually produce a systematic error, computational errors as a group tend to produce very small (about 0.1 percent) random errors in the estimate.[162]

The different sources of error, as noted above, can produce random or systematic (“bias”) errors. Random errors have the appearance of “noise” in the estimate, causing random year-to-year changes in the estimate as compared with (unobservable) actual emissions. Random errors might be caused by data collection and computation errors, the inherent imprecision of metering and measurement, and timing problems. Thus, it should be difficult to distinguish the “signal” of growing or declining emissions until the magnitude of the trend exceeds the “noise” from the random

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[162] Every year, as this report is prepared for publication, a number of computational errors that have crept into the report are detected and fixed. Sometimes, the detected errors have been present for more than one year. The errors that have been detected are typically very small (about 0.01 to 0.1 percent of emissions) and subtle, and they tend to both raise and lower estimated emissions. The EIA is not aware of any remaining computational errors, but it is assumed that any undetected errors generally are similar to, or smaller than, the errors that have been detected.

fluctuations. Since, in the case of U.S. energy data, rather small trends in the underlying data can be detected, it is likely that the aggregate magnitude of random errors in U.S. energy data is small, and, in particular, smaller than bias errors.

Bias errors will produce an error of approximately the same magnitude every year. If bias errors are small, they are not likely to affect the estimates of trends. Excluded sources and changes in definition produce bias errors. "Double counting" in activity data surveys will produce upwardly biased estimates of the activity; frame errors or other forms of undercounting will produce downwardly biased estimates. Because the EIA, like other statistical agencies, produces data by approximately the same methods every year, double counting and undercounting errors are likely to persist over time.

There is no reason to believe that the distribution of bias errors is symmetrical around the point estimate of the value. In fact, *a priori* or independently gathered information may indicate that the potential size and probability of the existence of bias errors may be skewed: for example, in EIA data it is likely that essentially all the transactions reported to the EIA actually occurred; however, it is possible that some transactions were never reported. Thus, EIA energy data are more likely to underestimate than to overestimate actual energy consumption. Further, because there are multiple surveys of energy production and consumption, undertaken for multiple purposes, the results of the surveys can help put bounds on the extent of possible bias errors.

Bias errors can be hard to detect, and it is hard to prove either the presence or absence of bias errors. The best ways of detecting them are to use multiple methods of estimating the source series and compare the results, or to determine the range of possible values from *a priori* information. Comparison methods usually can establish "ceilings" and "floors" for bias errors: that is, it is possible to demonstrate that if the bias error exceeds a certain percent, then a separate, independently collected series must also have a bias error of the same sign. An investigation of how the data are collected may also uncover information about the magnitude or scale of potential bias errors.

The reliability of emissions data varies by category and by source. In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. It is likely that the estimate of carbon dioxide emissions is accurate to within 5 percent, suggesting an emissions range from 1.3 billion to 1.5 billion metric tons.

Estimates of methane emissions are much more uncertain. The level of precision is probably on the order of 30 to 40 percent. Estimates of methane emissions are also likely to understate actual emissions, as a result of the exclusion of sources that are unknown or difficult to quantify.

Nitrous oxide emissions estimates are much more unreliable than carbon dioxide or methane emissions estimates, in part because nitrous oxide emissions have been studied far less than emissions from other sources and in part because the largest apparent sources of nitrous oxide emissions are area sources that result from biological activity, which makes for emissions that are highly variable and hard to measure or characterize. The uncertainty for the principal source of nitrous oxide emissions appears to be on the order of 100 percent, and there may be significant missing sources.

Carbon Dioxide

Sources of Uncertainty

Most carbon dioxide emissions estimated in this report result from the combustion of fossil fuels. The uncertainties in estimates of emissions from fossil fuel combustion can be divided into four types:

- **Uncertainties in the volumes of fuel consumed.** In general, volumetric fuel data are believed to be fairly reliable, plus or minus about 3 to 5 percent; estimates of total consumption by fuel are more reliable than estimates by sector or by particular product.
- **Uncertainties in the characteristics of fuel consumed.** Fuel data are collected on a volume or weight basis, but the density and energy content of fuels must often be estimated. The energy content of natural gas is reliable to 0.5 percent, but the reliability of energy content estimates for coal and petroleum products is lower.
- **Uncertainties in the emissions coefficients.** Emissions coefficients can be computed with a high degree of precision for a particular fuel sample on the basis of a laboratory analysis. If the characteristics of a fuel are difficult to measure accurately, however, the emissions coefficient for the sample fuel may not match the actual characteristics of the fuel consumed. The pipeline-quality natural gas coefficient is probably accurate to within 1 percent, but the reliability of the coal and petroleum product coefficients is lower, because they are more heterogeneous.

- **Uncertainties of coverage.** These uncertainties may arise from excluded or unknown sources of emissions.

Fuel Consumption

In general, energy statistics produced by the EIA are most accurate for energy industries that are highly concentrated and/or heavily regulated and least accurate for activities that are decentralized, with large numbers of producers or consumers, and for fuels that have many heterogeneous states. It is impossible to be certain about the absolute magnitude and distribution of errors in the energy data, but it is likely that most are bias errors rather than random sampling errors. The EIA collects the same data from nearly the same respondents every year (although survey frames are systematically updated), using nearly the same methods. Product flows that escape the coverage of the statistical system are likely to stay outside the statistical system from one year to the next. Similarly, if respondents make undetected definitional or computational errors (for example, misclassifying a petroleum product), they are likely to repeat their mistakes for prolonged periods.

There is indirect evidence in favor of the relative unimportance of random error in energy statistics, in the form of the relative lack of variability of the statistics compared with other economic time series. That most EIA surveys are censuses, with what is intended to be 100-percent coverage of eligible respondents, rather than small sample surveys, reduces the scope for random errors.

If, as is suspected, random error is relatively unimportant, then most of the error is bias error, made in essentially the same way every year. Therefore, while the level of U.S. emissions of carbon dioxide could be systematically lower or higher than reported here, the reported trends over time are more likely to be reliable than the uncertainties in the energy data would suggest. Since energy production and consumption are covered by multiple surveys, it is possible to use this information to gain insight into the possible uncertainties in the energy data.

Coal. Coal production and consumption data are based on weight—short tons of coal. Coal consumption by regulated electric utilities, including both tonnage and energy content, is universally reported to the EIA and the Federal Energy Regulatory Commission (FERC). In 1997, utility coal consumption accounted for about 89 percent of U.S. coal consumption.[163] There are likely to be only minor errors (around 1 percent) in reported utility coal consumption. Industrial, residential, and commercial coal consumption estimates are subject to potentially larger errors, especially in the counting of residential and commercial sector consumption; however, residential and commercial coal consumption is very small, and even large errors would have a negligible impact on emissions estimates. The statistical discrepancy for coal production (the difference between reported consumption and reported production less exports, plus imports, plus stock changes) averaged less than 8 million metric tons, or less than 1 percent of consumption, in the period 1991-1997.[164]

Natural Gas. Most natural gas is sold or transported by State-regulated local distribution companies. Excluding imports, the statistical discrepancy for natural gas has an average value of between 2 and 3 percent of consumption, with reported consumption usually smaller than reported production. This may imply some systematic source of under-reporting of consumption.

Inaccuracies in natural gas volumetric data come from inherent limitations in the accuracy of natural gas metering, as well as from the usual problems of misreporting and timing differences. For example, natural gas consumption by electric utilities, as reported by the utilities, averaged about a 10-percent difference from natural gas consumption as reported by natural gas sellers in 1995.[165]

Petroleum. U.S. petroleum consumption is estimated on the basis of “petroleum products supplied,” which means the volume of petroleum products shipped from primary storage facilities. Since there are only about 200 oil refineries in the United States, coverage of crude oil inputs and refinery outputs is generally complete. The EIA requires a detailed breakdown and accounting of petroleum products produced by refineries, including refinery fuel. There are several reporting anomalies in EIA petroleum data:

- Each year more crude oil is supplied to refineries than can be accounted for by oil production, imports, and stock changes. This “unaccounted for crude oil” averaged 145,000 barrels per day, or less than 1.0 percent of refinery supply, in 1997.[166] Unaccounted for crude oil is likely due to imprecisions in recorded crude oil production, import,

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[163] Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(97/4Q) (Washington, DC, May 1998), Table 37, p. 51.

[164] Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(97/4Q) (Washington, DC, May 1998), Table B1, p. 114.

[165] Energy Information Administration, *Natural Gas Annual 1996*, DOE/EIA-0131(96) (Washington, DC, September 1997), Table A2, p. 229.

[166] Energy Information Administration, *Petroleum Supply Annual 1997*, DOE/EIA-0340(97)/1 (Washington, DC, June 1998), Table S2, pp. 6, 7.

and stock change data. In EIA's *State Energy Data Report*, which presents consumption estimates, unaccounted for crude oil is included in consumption.

- Every year, several thousand more barrels per day of "unfinished oils" reach refineries than can be accounted for by sales and imports of unfinished oils.[167] In 1997, there were on the average 48,386 barrels per day of unaccounted for unfinished oils. The unfinished oil discrepancy is probably the result of asymmetric treatment of inter-refiner sales of unfinished oils. To the buyer, who knows the intended use of the product, it is motor gasoline or distillate fuel. To the seller, it is an unfinished oil. In the *State Energy Data Report*, the unfinished oil discrepancy is accounted for through an adjustment to "other oils." The implication is that total oil consumption figures are more reliable than the exact distribution of consumption across specific petroleum products. Overall, it is likely that petroleum consumption estimates are accurate to within 5 percent.

Nonfuel Use. Data for nonfuel use of petroleum products are more uncertain than those for total use of petroleum products. There are two main methods of estimating nonfuel use:

- Specialized petroleum products, such as petrochemical feedstocks, waxes and polishes, asphalt, and lubricants, are assumed to be dedicated to nonfuel use.
- Nonfuel use of conventional fuels is estimated on the basis of survey results from EIA's Manufacturing Energy Consumption Survey (MECS), with additional detail from trade association data and from known specific nonfuel uses (such as fertilizer feedstocks for natural gas).[168] MECS is a sample survey conducted only at 4-year intervals, with the sample optimized to detect the use of fuels for heat and power. Using MECS to measure nonfuel use requires interpolating between sample years and correcting for sampling problems associated with reported nonfuel use.

The main uncertainty in estimating carbon sequestered from nonfuel use is not the amount of product used but the fate of its carbon. The sequestration percentages used in this report are estimates, originally based on the typical fate of a particular class of products. The actual distribution of nonfuel uses of products is not always known with precision and could vary considerably from the "typical" usage; however, because sequestration through nonfuel use corresponds to only about 5 percent of total emissions, even large variations in the amount sequestered would have a small effect on estimated total emissions.

Conversion Factors

EIA oil and gas data are collected in volumetric units—barrels of oil and billion cubic feet of gas. Carbon emissions factors for fossil fuels usually take the form of tons of carbon per unit of energy content. Emissions factors are computed by dividing the carbon content (by weight) of a particular fuel by its energy content. Thus, in order to match an emissions factor to a fuel accurately, it is necessary to know its energy content with precision; and in the case of fuel quantity based on volumetric data, it is also necessary to know the density of the fuel. Each step that transforms the data from native units into more useful units inevitably reduces the precision of the resulting data, because the conversion factors are themselves statistical estimates or extrapolations, which may not precisely match the actual composition of the fuel.

Coal. Coal data are collected by State, coal rank, and weight (short tons). Electric utilities are asked to report both the rank and the energy content of the coal they burn. Since, in principle, utilities need to know the energy content of the fuels they purchase with precision, the energy content data should be fairly accurate. On the other hand, there is considerably more uncertainty in the rank or energy content of coal distributed outside the utility sector, which in 1996 accounted for about 11 percent of U.S. coal consumption.

The quality of coal can vary considerably within States and within a particular rank. Lignite, for example, is defined as containing 6,300 to 8,300 British thermal units (Btu) per pound, a range of about 15 percent. Subbituminous coal, by definition, has a range of 8,300 to 11,500 Btu per pound.[169] Thus, there may be errors of up to 15 percent in the industrial and residential/commercial coal conversion factors. On the other hand, residential/commercial and industrial coal consumption accounts for only about 5 percent of total U.S. energy-related carbon emissions, and even large errors would have only a small impact on the ultimate estimates.

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[167] Energy Information Administration, *Petroleum Supply Annual 1997*, DOE/EIA-0340(97)/1 (Washington, DC, June 1998), Table 2, p. 34.

[168] Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3.

[169] Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 252, 255.

Natural Gas. The composition of natural gas also varies considerably. In a recent survey of several thousand gas samples taken from local distribution companies around the United States, the Btu content ranged from 970 to 1,208 Btu per thousand cubic feet.[170] However, 80 percent of the samples fell within a much narrower range of 1,006 to 1,048 Btu per thousand cubic feet. Further, the average and median values of the samples fell within 0.3 percent of the national-level figure reported in EIA's *Natural Gas Annual*. This comparison suggests that EIA data on the energy content of natural gas are accurate to within 0.5 percent. This is not surprising, because local distribution companies monitor the energy content of natural gas to ensure adherence to contractual specifications, and they report the average energy content to the EIA.

Petroleum. The energy content of petroleum products varies more by volume than by weight. The density and the energy content of petroleum products are rarely measured by producers or consumers, and frequently they are not known with precision. Electric utilities measure the energy content of the residual oil they burn and report it to the EIA. Liquid petroleum gases (propane, butane, and ethane) are pure compounds, and their energy content can be computed directly.

Liquid transportation fuels (jet kerosene, gasoline, and diesel fuel) are complex mixtures of many compounds, whose physical properties can vary considerably. Neither their density nor their energy content is measured by consumers or directly defined by product specifications. The EIA estimates the energy content of these fuels on the basis of standard or "typical" values for each product. The standard energy contents for motor gasoline and kerosene-based jet fuel are drawn from a 1968 report produced by the Texas Eastern Transmission Corporation.[171] The energy content of distillate fuel oil is drawn from a Bureau of Mines Standard adopted in January 1950.[172] Jet fuel and diesel samples obtained for this report showed an average energy content that differs from EIA estimates by about 2 percent. Samples of motor gasoline analyzed by the National Institute of Petroleum and Energy Research displayed an average energy content that differs from EIA estimates by less than 0.5 percent. Reformulated gasoline, with the additives MTBE, ETBE, and TAME typically representing about 10 percent of its volume, can be expected to have an energy content about 1 percent lower than the energy content of standard gasoline. However, when collecting and disseminating motor gasoline data in units of energy, the EIA does not use a distinct conversion factor for reformulated gasoline.

Carbon Emissions Coefficients

Carbon emissions coefficients are calculated by dividing the carbon content of a particular fuel (for example, 0.85 metric tons of carbon per metric ton of fuel) by the energy content of that fuel (for example, 43 million Btu per metric ton) to produce an emissions coefficient (in this example, 19.8 million metric tons of carbon per quadrillion Btu). Both the energy content and the carbon content of the fuel are subject to a degree of uncertainty. The carbon content of fuels has only an indirect and general bearing on their economic value and, consequently, is not necessarily collected by fuel producers or consumers. Although coefficients for coal and natural gas rely on analyses of a large set of fuel samples, coefficients for several petroleum products are based on "typical" or "representative" values, which may or may not perfectly reflect the underlying composition of the fuel. Variation in carbon content is limited to plus or minus 5 percent by the standard ratios of carbon to hydrogen in the hydrocarbon compounds that compose petroleum.[173]

Coal. There are large variations in the carbon and energy content of coals in different parts of the United States. Lignite may have as little as 12.6 million Btu per ton and contain 36 percent carbon, and anthracite may have as much as 98 percent carbon and an energy content as high as 27 million Btu per ton.[174] The carbon and heating values of coal are, in general, controlled by two factors:

- The ratio of flammable materials (carbon, hydrogen, and sulfur) in coal to nonflammable impurities (moisture, ash, etc.)
- The ratio of carbon to hydrogen and sulfur within the flammable portion of the coal.

Most of the gross variation in both energy and carbon content (for example, between lignite and anthracite) is

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[170] W.E. Liss et al., *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States* (Chicago, IL: Gas Research Institute, March 1992), p. 14.

[171] Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 497.

[172] Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 496.

[173] Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), pp. 78-80.

[174] Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 247-248, 252, 255.

due to variations in nonflammable impurities. Consequently, if the Btu content of coal is estimated accurately, most of the variation in the carbon content is removed.

There is, however, residual uncertainty about the ratio of carbon to hydrogen and sulfur in particular coals. The carbon content of any particular coal sample can be determined by chemical analysis, but characterizing the average carbon content of national coal production creates some uncertainty. For this report, the EIA relied on chemical analyses of several thousand coal samples, sorted by State of origin and coal rank, to compute national weighted average emissions coefficients (in million metric tons of carbon per quadrillion Btu) for each coal rank.

Natural Gas. Natural gas also varies in composition, but the range of variation is much smaller than that for coal. The emissions coefficient used in this report was based on an analysis of some 6,743 recent samples of U.S. natural gas. While there is some residual uncertainty about the exact carbon content of average U.S. natural gas, this uncertainty is on the order of 1 percent or less.

Petroleum Products. Crude oil is refined into a wide range of petroleum products, each presenting a different set of uncertainties. In general, the carbon content of petroleum products increases with increasing density. Uncertainties in emissions coefficients arise primarily from estimating the wrong density for a fuel or from mismatching the carbon and energy content of a particular fuel. The emissions factors for liquefied petroleum gas (LPG) and motor gasoline are probably accurate to within 1 to 2 percent. Coefficients for jet fuel and diesel fuel are probably accurate to within 2 to 4 percent, with much of the uncertainty centered in the standard heat contents used. The estimate for residual fuel is more uncertain but is probably accurate within 3 to 5 percent, as there are remaining uncertainties about the exact density and carbon content of the fuel.

The uncertainty for some minor petroleum products remains large, in some cases because it has proven difficult to identify exactly how reporters define particular product categories. Products with large remaining uncertainties include petrochemical feedstocks (density and portion of aromatics), lubricants, and waxes and polishes. The uncertainty of the emissions coefficients for these products is probably on the order of 10 percent. Because these products share a large nonfuel use component, their impact on the total carbon emissions figure is muted. Still gas is a highly variable byproduct of the refining process, which is then described as a petroleum product. Thus, the estimated emissions coefficient for still gas may vary by as much as 25 percent.

Adjustments to Energy

U.S. Territories. Energy data for U.S. territories present certain problems. Published petroleum data for Puerto Rico and the Virgin Islands are considerably less detailed than those for the mainland United States. In particular, there is no estimate of nonfuel use for these territories, and much of the petroleum consumption that could potentially be considered nonfuel use is lumped together into “other petroleum.” Hence, the reliability of the emissions estimates is lower than that of petroleum emissions estimates generally.

Flare Gas. Estimates of emissions from flare gas are subject to uncertainty from two sources: estimates of the volume of gas flared, and the application of an appropriate emissions coefficient. Estimates of gas flared are based on State-reported volumes of gas “vented or flared” and a State-by-State estimate of the portion flared. The 1996 estimate of all vented and flared gas was 269 billion cubic feet. States may define “vented” or “flared” gas differently. This suggests that estimates may be upwardly biased by the inclusion of nonhydrocarbon gases, such as hydrogen sulfide or carbon dioxide, in the statistics. Anecdotal reports from Wyoming, the State that represents approximately half of the estimated gas flared, indicate that most flaring is of nonhydrocarbon gases and that carbon dioxide emissions may be lower than estimated.

The emissions coefficient applied to flare gas represents the average coefficient for natural gas samples with heat contents between 1,100 and 1,127 Btu per standard cubic foot. The EIA estimates the heat content of “wet” gas at 1,109 Btu per standard cubic feet.[175] Anecdotal evidence suggests that most flared gas is flared at gas processing facilities, where the wet gas energy content would be representative. However, if flared gas is mostly “rich” associated gas with a heat content between 1,300 and 1,400 Btu per standard cubic feet, the current coefficient seriously biases the estimates downward. Alternatively, it is possible that flare gas from treatment plants is “off spec” gas with a large content of hydrogen sulfide or inert gas and, hence, an emissions coefficient lower than the one actually used.

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[175] Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), p. 320.

Other Sources of Carbon Emissions

The principal source of uncertainty in cement manufacture is the lime content of cement, which is estimated to within about 3 percent. There may also be imitations on the inherent accuracy of the Interior Department data used to calculate the estimate.

A second source of uncertainty, common to all the industrial estimates, is the use of stoichiometric computations to estimate emissions. This method calculates an emissions factor on the basis of a chemical reaction known to have taken place. It assumes, in effect, that the product (cement, lime, soda ash) is 100 percent pure, and that no raw materials are wasted in its production. In practice, impurities in the output would tend to reduce emissions below the stoichiometric estimate, whereas "wastage" of raw materials would tend to raise emissions above the estimate.

Excluded Sources

Appendix D lists several sources of emissions that are excluded because of uncertainty. Emissions from the consumption of international bunker fuels are also excluded in accord with international convention. Sources excluded because of insufficient data include, for example, emissions from natural gas plants. Also, this year, because of another reversal in the sign of the estimate (the 1996 value is negative), EIA has excluded unmetered gas. Whatever the sign, the impact on total emissions is likely to be very small. Taking what is known about all excluded sources, additional emissions would probably be less than 10 million metric tons, or less than 1 percent of estimated emissions. Nonetheless, their exclusion does slightly bias the estimate downward. There are almost certainly other sources of carbon emissions unknown to the authors of this report. There is no way to estimate the impact of such unknown additional sources.

Methane

Estimates of methane emissions are, in general, substantially more uncertain than those for carbon dioxide. Methane emissions are rarely systematically measured. Where systematic measurements have been made, data are restricted to a small portion of the emission sites and a few years. In order to use these data to estimate emissions for the full population of emitters and to develop time-series emissions estimates, scaling mechanisms and sampling techniques must be applied, introducing additional error.

Where no systematic measurements have been made, estimation methods rely on a limited set of data applied to a large and diverse group of emitters. However, as additional data comes available each year, uncertainty in emissions estimates declines or, at a minimum, is more clearly delineated. In this year's report, additional information on emissions from coal mines, oil and gas operations, and dairy cattle was incorporated into the estimates, reducing uncertainty for those sources.

Coal Mining

Emissions from coal mines are currently the fourth-largest source of methane emissions in the United States—behind landfills, oil- and gas-related emissions, and domestic livestock—and they account for approximately 11 percent of national methane emissions. Methane emissions from coal mining have five sources: ventilation systems in underground mines, degasification systems in underground mines, surface mines, post-mining activities, and abandoned or closed mines. Only the first four are included in emissions estimates, because data on emissions from abandoned mines are lacking. The uncertainty associated with estimates of emissions from each of the sources included varies considerably and according to the year of the estimate. The exclusion of emissions from abandoned mines results in a downward bias in the estimates, but the size of the bias is unknown. The overall uncertainty of the EIA estimates for emissions from coal mines is probably about 35 percent.[176]

Emissions from ventilation systems in the Nation's gassiest mines are measured on a quarterly basis by the Mine Safety and Health Administration (MSHA). A database, developed from these reports for all mines emitting more than 100,000 cubic feet of gas per day was compiled by the Bureau of Mines for the years 1980, 1985, 1990 and 1993. The Atmospheric Pollution Prevention Division of the U.S. Environmental Protection Agency (EPA) has since compiled a similar database for 1994, 1996, and 1997. Although the measurements themselves should be reasonably accurate, each measurement represents a point in time. Variations in methane emissions across time (e.g., resulting from changes in operating practices) suggest an uncertainty in the range of 10 to 40 percent.

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[176] S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

Estimates of emissions from the ventilation systems of nongassy mines are scaled to emissions estimates for 1988 developed by the EPA.[177] The EPA estimates emissions from nongassy mines at 2 percent of total emissions from the ventilation systems of underground coal mines. Thus, an error as high as 100 percent for this source would add less than 1 percent to the total estimate.

Emissions from degasification systems have been the single largest source of uncertainty in estimates of emissions from coal mines. Previous editions of this report scaled emissions to estimates of emissions for 1988 developed by the EPA. Measurements of emissions were limited to a few mines, and the remainder of the estimate was based on known emissions from ventilation systems and estimated recovery efficiencies of degasification systems. The recovery efficiencies have an uncertainty in the neighborhood of 20 percent. This year's report uses mine-by-mine degasification data collected by the Environmental Protection Agency for the years 1993-1996.[178] The inclusion of these data should reduce the uncertainty associated with estimate of degasification emissions.

Reliable measurements of emissions from surface mines are available for only five sites. Thus, estimates for this report were based on an emissions range supplied by the Intergovernmental Panel on Climate Change (IPCC).[179] The range of emissions suggested by the IPCC implies an uncertainty range of plus or minus 75 percent. However, estimates of emissions extrapolated from the five measured sites suggest an uncertainty level of less than 10 percent.[180] Assuming the larger uncertainty level would add only about 10 percent to the overall uncertainty of estimates of emissions from coal mines, because the volume of emissions from surface mines is relatively insignificant.

Emissions from post-mining activities are also estimated on the basis of an emissions range supplied by the IPCC, which implies an uncertainty in the area of plus or minus 60 percent. However, the magnitude of emissions from this source is similar to that of emissions from surface mines, thus also contributing about 10 percent to the overall uncertainty of coal mine emissions estimates.

Oil and Gas Operations

Emissions estimates from oil and gas operations are calculated on the basis of activity data and emissions for 86 separate gas industry process components. A recent study funded jointly by the EPA and the Gas Research Institute (GRI) provided point-in-time activity and emission factor estimates for each component during 1992.[181] To extrapolate estimates for other years from 1990 through 1997, activity data for each process component were associated with and scaled to a widely available data series, such as gross gas withdrawals or pipeline miles. The derived activity data were then applied to the 1992 emissions factor reported by EPA/GRI.

Despite capitalizing on an extended field sampling program and a statistical framework to meet predetermined accuracy goals, the EPA/GRI study still was forced to rely on a nonrandom sampling method that may not have been fully representative of the sample universe. Thus, there is uncertainty associated with both the activity factors and the emissions factors used in the original estimate. The uncertainty is further magnified by any additional error introduced by the scaling methods used for the activity data.

The uncertainty associated with activity data for 1992 varies dramatically across individual components, from as little as 2 percent to as much 1,114 percent. The uncertainty for emissions factors ranges from 5 percent to nearly 4,000 percent. These uncertainties are not necessarily correlated, and when they are combined to generate an emissions estimate from each component, the uncertainties are between 17 percent and 4,000 percent. On the other hand, because the largest emissions sources are associated with lower levels of emissions, the overall uncertainty of the national estimate is plus or minus 33 percent, probably increasing to on the order of plus or minus 40 percent after scaling activity data to more common industry metrics.

This report excludes methane emissions from the venting of gas from associated wells. The EIA collects data on gas vented or flared as reported by State agencies. The data reported by State agencies capture venting at many stages of the natural gas system. Thus, much of

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[177] U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

[178] U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997).

[179] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.108, web site www.iea.org/ipcc/invs6.htm.

[180] S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

[181] M.R. Harrison and R.M. Cowgill, *Methane Emissions From the Natural Gas Industry*, Prepared for the Gas Research Institute and the U.S. Environmental Protection Agency (June 1996).

the reported venting is already captured under the existing EPA/GRI estimation method. Further, anecdotal information from Wyoming indicates that much of the gas reported to be vented is actually non-hydrocarbon gases that do not contribute to methane emissions. It is certain, however, that some methane is vented from associated gas at oil wells. The exclusion of such venting biases emissions estimate downward, perhaps by as much as 5 percent.

Additional uncertainty is associated with estimates of methane vented at "stripper wells." Associated natural gas production at oil wells producing less than 10 barrels per day may be at pressures and volumes too low to be of commercial value. The gas may be vented, or it may evaporate from storage tanks. Such emissions are not captured in any data series, and their magnitude is impossible to estimate. Stripper wells contribute 14 percent of U.S. oil production.

Combustion-Related Emissions

Most methane emissions from stationary combustion are the result of wood burning in residential woodstoves. Because estimates of wood consumption and of the condition and efficiency of residential woodstoves are highly uncertain, estimates of emissions from this source may vary by more than an order of magnitude.

Methane emissions from mobile combustion may be larger than the estimate in this report, but it is unlikely that they are significantly smaller. Emissions factors for mobile transportation assume a well-maintained fleet. A fleet of inadequately maintained vehicles may have as much as 10 times the level of emissions of a fleet of well-maintained or new vehicles. Although much of the U.S. fleet is well-maintained, a portion is old and/or poorly maintained.

Landfills

Estimates of methane emissions from landfills were broken into two sources: emissions from waste contained in 105 mostly large landfills with gas recovery systems and emissions from waste contained in all other landfills. Uncertainties associated with estimates of emissions for these two sources differ substantially.

Emissions for many of the 105 mostly large landfills were estimated for 1992 on the basis of volumes of gas recovered and the efficiency of gas recovery.[182] Gas recovery efficiency was estimated with an associated uncertainty of plus or minus 25 percent. For years other than 1992, emissions from this source were estimated by using a model of landfill waste emissions that is benchmarked to the 1992 data. The model parameters include a low yield and high yield scenario that imply an uncertainty of 35 percent.

Emissions from all other landfills were also estimated from an emissions model, with parameters that could vary by 30 percent from the mean. A crucial input into the model is the amount of waste in place, which was calculated from estimates of waste landfilled annually between 1960 and 1997 and a regression equation to "backcast" waste flows from 1940 to 1960. The range of published estimates for years in which multiple sources were available suggests an uncertainty in the neighborhood of plus or minus 33 percent, and the error associated with the regression equation probably adds another 2 to 10 percent uncertainty.[183]

The ratio of waste in place in the 105 landfills to that in all other landfills was assumed to remain constant over time. This may be misleading, because the total number of landfills has been declining, with greater shares of waste believed to be directed toward larger landfills. Because those landfills with measured emissions for 1992 are likely to have higher-than-average emissions per ton of waste, the estimates for earlier years may be biased upward.

Domestic and Commercial Wastewater Treatment

Methane emissions from domestic and commercial wastewater treatment were estimated by IPCC's simplified approach,[184] which is based on the following assumptions: (1) each person contributes 0.5 kilogram per day of BOD_5 to municipal wastewater; (2) 15 percent of wastewater is treated anaerobically; and (3) anaerobic treatment yields 0.22 kilogram of methane per kilogram of BOD_5 treated. These assumptions were derived for developed countries in general, and there is considerable uncertainty about their specific applicability to the United States.

Per capita organic loadings of municipal wastewater in developed nations ranges from 0.024 to 0.091 kilogram BOD_5 per day. Organic loadings depend on such

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[182] S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, "Estimate of Methane Emissions from U.S. Landfills," Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994).

[183] Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States: 1994 Update* (prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response); and "The State of Garbage in America," *Biocycle* (various years).

[184] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 6.15-6.23, web site www.iea.org/ipcc/invs6.htm.

factors as the amount of kitchen wastes discharged into sewers and the degree to which industrial wastewater is discharged into municipal wastewater treatment systems. Wastewater treatment methods that are potential sources of methane include anaerobic digesters, facultative and anaerobic lagoons, and septic tanks. However, reliable information on the quantity of wastewater treated by each of these methods is not available. The IPCC emissions factor of 0.22 kilogram of methane per kilogram of BOD_5 is based on an estimate for lagoons in Thailand.[185] The applicability of this factor to treatment methods in the United States is uncertain.

A further source of uncertainty is the ultimate fate of methane generated from wastewater in the United States. As in the case of landfill methane, wastewater methane generated in sewage treatment plants is often combusted to control odors or emissions of volatile organic compounds. Conceptually, the amount of methane combusted should be deducted from estimated emissions, but the EIA is not aware of any information on the amount or extent of combustion of off-gases from sewage treatment plants.

Enteric Fermentation in Domesticated Animals

Estimates of methane emissions from enteric fermentation in domesticated animals are less uncertain than those for other sources of methane emissions. Emissions estimates are a function of an emissions factor for each animal group, based on their diet and energy usage multiplied by their population. Animal population data have recently been revised by the U.S. Department of Agriculture, and the magnitude of revisions suggests that population estimates are likely to be accurate within 5 percent. The energy requirements and diets of cattle—by far the largest source of emissions from enteric fermentation—have been carefully studied. For dairy cattle, energy requirements are largely a function of milk production. In contrast to previous editions of *Emissions of Greenhouse Gases in the United States*, which used national population data and average emissions factors for all animals, this year's report uses State-level data and regional emissions factors for dairy cattle, scaled to milk productivity provided by the EPA.[186] Because cattle feed and milk productivity vary by region, this modification should somewhat reduce uncertainty.

There is also some uncertainty associated with the average size of cattle, which could affect the animals' energy requirements. Cattle sizes have changed rapidly over the past decade in response to market forces. This report uses slaughter weights as a proxy for average animal size and scales emissions factors for beef cattle to animal size, a method that may be imperfect. The slaughter sizes vary over time by approximately 33 percent. There is some uncertainty associated with estimates of the energy requirements of other animals, but even if this uncertainty were as high as 50 percent, the impact on the overall estimate would be no more than 3 percent.

Solid Waste of Domesticated Animals

Uncertainty in estimates of animal populations is on the order of 5 percent or less. Emissions are largely a function the amount of waste an animal produces. The amount of waste produced is a function of size, productivity, and diet. Thus, changes in animal sizes, which are difficult to monitor, create additional uncertainty. As discussed above, slaughter weights have been used as an imperfect measure of changes in the size of beef cattle. This proxy measure varies by about 33 percent over time.

The maximum amount of methane that a given amount of an animal's waste can produce under optimal anaerobic conditions can be measured fairly accurately in the laboratory. The share of that production realized under various waste management regimens is much more uncertain. Waste management systems and the portion of potential methane emissions realized vary across States. This is the first edition of *Emissions of Greenhouse Gases in the United States* in which State-level population data and methane conversion factors for the waste of dairy cattle provided by the EPA[187] have been used.

Emissions also vary with ambient air temperatures and, depending on the waste management system, may change by anywhere from 1 to 60 percent. For this report, all animal waste was assumed to be managed at air temperatures between 59 and 77°F. Overestimating the average temperature at which waste is managed would bias emissions estimates upward.

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[185] U.S. Environmental Protection Agency, *International Anthropogenic Methane Emissions: Estimates for 1990,* EPA 230-R-93-010 (Washington, DC, January 1994), p. 10-15.

[186] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[187] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

Wetland Rice Cultivation

There are large uncertainties associated with the estimate of methane emissions from wetland rice cultivation. Emissions estimates are based on several studies of rice paddies in the United States, which provide daily emissions rate ranges. Studies have shown large seasonal and time-of-day variations in methane flux. Many variables affect methane production in rice fields, including soil temperature, redox potential, and acidity; substrate and nutrient availability; addition of chemical and/or organic fertilizers; rate of methane oxidation; and rice plant variety. The wide range of emissions provided by different researchers suggests an uncertainty of several hundred percent.[188] The lack of data for emissions from Florida during 1997 biases emissions downward by about 1 percent.

Crop Residue Burning

Estimates of emissions from the burning of crop residues are calculated on the basis of a carbon content of about 45 percent of dry matter, as recommended by the IPCC,[189] and a 3-percent burn rate for all crop residue except rice in California, as recommended by the EPA.[190] The 3-percent rate is a significant reduction from the 10 percent used in previous editions of *Emissions of Greenhouse Gases in the United States* and has mitigated a potential source of upward bias. The carbon content probably is accurate to plus or minus 10 percent.

Chemical Production

Estimates of methane emissions from chemical production are highly uncertain because of the wide variety of production processes and inputs. Organic chemical production requires the cracking and reforming of hydrocarbon bonds. How the bonds crack and reform depends on several variables, including the composition of the feedstock, the temperature of the reaction, the catalyst used, and the reaction vessel. As a result, the quantities of products and byproducts, including methane, vary. Methane may be released through leaks in seals and valves. Therefore, methane emissions are dependent on the operation and maintenance practices of the producer.

Iron and Steel Production

There is substantial uncertainty associated with estimates of methane emissions from iron and steel production, with the plausible range of estimates ranging from 80 percent below the point estimate presented in this report to 100 percent above the point estimate. Several factors mitigate methane emissions from iron and steel production. The pollution controls used on coke ovens to prevent emissions of volatile organic compounds usually eliminate methane as well. Exhaust gases from blast furnaces that are typically captured and used for fuel contain methane. Because the emissions factors used in this report are global emissions factors provided by the IPCC,[191] they may not accurately portray the level of emission controls found in U.S. plants. Further, the efficacy of pollution control systems is likely to vary with operation and maintenance techniques.

Excluded Sources

Appendix D lists several sources excluded because of excessive uncertainty or insufficient data. Known sources excluded from methane emissions estimates are industrial wastewater, associated gas at oil wells, abandoned coal mines, industrial landfills, and open dumps. There are other sources of methane that have yet to be identified and thus are absent from emissions estimates. Excluded sources would invariably add to total emissions, but the magnitude of the additions is impossible to estimate.

Nitrous Oxide

Many sources of nitrous oxide emissions are difficult to quantify, and estimates are highly uncertain. Nitrous oxide has been viewed as a minor contributor to overall U.S. greenhouse gas emissions, and until recently few resources have been devoted to improving measurement and estimation methods. However, the inclusion

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[188] R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux from a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209; C.W. Landau and P.K. Bolich, "Methane Emissions from Louisiana First and Ratoon Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48; R.L. Sass, F.M. Fisher, S. Lewis, M. Jund, and F. Turner, "Methane Emissions from Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135; R.L. Sass, F.M. Fisher, and Y.B. Wang, "Methane Emissions from Rice Fields: The Effect of Floodwater Management," *Global Biogeochemical Cycles*, Vol. 6 (1992), pp. 249-262.

[189] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.67-4.86, web site www.iea.org/ipcc/invs6.htm.

[190] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1996*, Review Draft (Washington, DC, March 1998), web site www.epa.gov/globalwarming/inventory/1998-inv.html.

[191] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.22, web site www.iea.org/ipcc/invs6.htm.

of nitrous oxide in the Kyoto Protocol and revised emissions factors that doubled its share of U.S. emissions have increased the attention given to nitrous oxide. As a result the uncertainty of future estimates is likely to be reduced. Estimates of emissions from the largest source of nitrous oxide, nitrogen fertilization of agricultural soils, have doubled as a result of methodological revisions.

Mobile Sources

Nitrous oxide emissions from mobile sources are, after nitrogen fertilization of soils (see below), one of the largest sources of uncertainty in the total estimate. Nitrous oxide is emitted from motor vehicles equipped with catalytic converters, but the conditions under which the emissions are produced are not well defined. Research evidence indicates that catalytic converters can convert nitrogen oxides (NO_2) into nitrous oxide (N_2O) when they are operating at relatively low temperatures, but that full conversion to ordinary nitrogen (N_2) occurs when the catalytic converter is operating at its normal operating temperature.

Estimating national-level nitrous oxide emissions from this source thus presents a daunting challenge, because emissions depend on:

- Whether or not vehicles are equipped with catalytic converters, and with what type of catalytic converter
- What portion of the vehicle fleet has properly functioning catalytic converters
- National average “driving cycles,” indicating what portion of the time the national vehicle fleet is driven with warm (but neither hot nor cold) catalytic converters.

Last year, the IPCC published new emissions factors that were some four times higher than the emissions factors used in last year’s edition of *Emissions of Greenhouse Gases in the United States*. The origin of the new emissions factors lies in a confluence of two events: scientific research indicated significant missing sources of nitrous oxide; and an emissions report published by the Canadian government, based on recent research,[192] indicated much higher Canadian emissions of nitrous oxide from mobile sources than had been anticipated. The research subsequently found its way into the revised IPCC guidelines and into work undertaken by the EPA’s Office of Policy, Planning, and Evaluation. The EPA’s Office of Mobile Sources reacted by mounting a program of testing U.S. motor vehicles for nitrous oxide emissions in June and July 1998. Preliminary results, published in August 1998, recommend emissions factors for U.S. use that are about 25 percent higher than those used by the EIA in 1997 and about one-third the magnitude of those recommended by the IPCC.[193]

The work done by EPA’s Office of Mobile Sources indicated that the linkage between the Canadian research and the emissions factors actually used in the Canadian inventory was weak, and that the emissions factors used in the Canadian inventory were at least 50 percent higher than would be indicated by the underlying research. Further, the Canadian tests were undertaken using test gasoline with sulfur levels at least twice the U.S. average, and the U.S. testing indicated that, by affecting the catalytic converter, the higher sulfur content may have greatly increased nitrous oxide emissions. However, all the tests of motor vehicles for nitrous oxide emissions reported in the literature combined involve fewer than 50 vehicles, and the sampling of the vehicles is neither random nor representative. Vehicles have also been tested under a limited range of conditions. Test results to date have been, as noted, highly variable, and we do not yet have a complete understanding of the causes of motor vehicle nitrous oxide emissions.

The biggest single influence on nitrous oxide emissions is how the vehicle is driven or, at the national level, the characteristics of the national average trip. In the Canadian tests, automobiles driven in the “highway mileage test” (used to calculate the figures shown on the “highway mpg” sticker on new cars) had emissions per kilometer about one-fourth the level of *the same vehicles* driven over the “Federal test program” (used to show compliance with Federal emissions standards). The highway mpg test uses a warm start, an average distance of 20 miles, and an average speed of 40 mph. The Federal test program simulates a 9.5-mile, stop-and-go, 19 mph average from a cold start. It would be reasonable to conclude that a high level of emissions occurs at the cold start, which is then allocated over some number of miles. The longer the trip, the lower the emissions per mile.

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[192] A. Jaques, F. Neitzert, and P. Boileau, *Trends in Canada’s Greenhouse Gas Emissions (1990-1995)* (Ottawa: Environment Canada, October 1997, pp. 23-24. The cited research was: V. Ballantyne, P. Howes, and L. Stephanson, *Nitrous Oxide Emissions From Light Duty Vehicles*, SAE Technical Paper 940304 (March 1994).

[193] U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide From Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), web site www.epa.gov/oms/climate.htm. The author of this report is Harvey Michaels.

The IPCC emissions factors are calculated in grams of nitrous oxide per kilometer driven, but the actual relevant emissions would seem to be grams of nitrous oxide per cold start. If the length and character of the "national average trip" approximates the trip used to calculate the emissions factor, then the emissions factor gives the correct result. As it turns out, the EPA designed the Federal test program to resemble the "national average trip," as determined by the U.S. Department of Transportation's National Personal Transportation Survey. This implies that the EPA's emissions factors may be reasonable as a first approximation. There are, however, several potential sources of uncertainty:

- **Potential for the wrong model of emissions.** It may turn out that a "per unit fuel consumption" or a "per trip" model of emissions produces more accurate results than the current "per kilometer" method. This is particularly the case in that national gasoline consumption is easier to measure than national vehicle miles traveled.

- **Uncertainties about the correct emissions factors.** At present, there is a tremendous (fourfold) variation in observed emissions factors (measured in grams per kilometers) across different catalytic-converter-equipped vehicles and across the same vehicle subject to multiple tests or different tests. Under the circumstances, there can be little assurance at present that the emissions factors that are being used are closely representative of on-road emissions factors.

- **Uncertainties about activity data.** At present, the EIA emissions estimates are based on estimates of national vehicle miles traveled, drawn from the Federal Highway Administration (FHWA) and partitioned by vehicle type and vintage. Total national vehicle miles traveled are drawn from a variety of State surveys of varying quality, undertaken for varying purposes. In recent years, the States have experienced great difficulty in accurately partitioning data between cars and light trucks, given recent increases in sales of light trucks as automobile substitutes. The partitioning is important for nitrous oxide emissions, because light-duty vehicle emissions factors are about 50 percent higher than automobile emissions factors. The FHWA recently revised the "split" between cars and light trucks for data back to 1993 but has not revised 1992 and earlier data.

- **Variations by model year.** The new emissions factors vary considerably by model year, with very low factors for pre-1983 model cars, higher factors for 1983-1995 model cars, and lower factors for post-1996 model cars. Thus, the partitioning of vehicle miles traveled between cars and light trucks, and by model year, is a source of added uncertainty.

In summary, the largest uncertainty is associated with the emission factors themselves. The range of reported emissions factors might vary by as much as a factor of 4. Choosing the incorrect model of emissions could also produce large (but probably less than 100 percent) errors. The problems associated with the activity data are of smaller magnitude, but still substantial. An imprecise partitioning of vehicle miles traveled between cars and trucks could push emissions up or down by perhaps 10 to 20 percent. The estimate of total vehicle miles traveled is more reliable than its components, particularly in view of the number of independent checks (such as gasoline consumption) that prevent the aggregate data from wandering too far from the (unobservable) actuals.

Stationary Source Combustion

As the result of improved studies, emissions factors recommended by the IPCC are now limited to one value for each fuel type, regardless of application. Although the emissions factor for coal is 1.4 kilograms of nitrous oxide per terajoule of energy input, emissions may range from 0 to 10 kilograms. For oil, the recommended emissions factor is 0.6 kilogram, with a possible range of 0 to 2.8 kilograms. The range is smallest for natural gas (0 to 1.1 kilograms), with 0.1 kilogram as the suggested factor.[194] The emissions factors were derived from studies of "conventional" combustion facilities (those equipped with burners and grate combustion, with flame temperatures well above 1,000^{o}C).

The underlying "problem" with estimating nitrous oxide emissions from combustion is that high-temperature combustion, by itself, apparently does not create much nitrous oxide, and it may destroy nitrous oxide. Under poorly understood circumstances, however, nitrogen oxides (NO, NO_2, and NO_3), which are combustion byproducts, may react to form nitrous oxide in exhaust stacks, sample bottles used for testing emissions, or perhaps in the atmosphere after being emitted. The existence of this circumstance has made it difficult to measure emissions accurately and raises the possibility that stationary combustion, through the medium of NO_x emissions, may ultimately prove to be a larger source of nitrous oxide than is currently believed.

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[194] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.36, web site www.iea.org/ipcc/invs6.htm.

Solid Waste of Domesticated Animals

Similar to methane emissions from the solid waste of domesticated animals, nitrous oxide emissions are a function of animal populations, volatile solids production, the nitrogen content of the volatile solids, and how efficiently the manure management system used converts nitrogen to nitrous oxide. Uncertainty in estimates of animal populations is on the order of 5 percent or less. Volatile solids content, the nitrogen content of the waste of each species, manure management systems, and nitrogen to nitrous oxide conversion rates are from the IPCC.[195] The IPCC emissions factors were derived from limited data and are global averages, which may differ from U.S. averages. Also, the IPCC factors show an identical nitrogen to nitrous oxide conversion rate for both anaerobic lagoons and liquid/slurry management systems. These systems are likely to have different nitrous oxide yields.

Nitrogen Fertilization of Agricultural Soils

This year's report includes higher levels of emissions from nitrogen fertilization of agricultural soils. Part of the increase comes from a 25-percent higher emissions factor for all sources, but most of the increase in estimated emissions results from a broader accounting of the sources of nitrogen placed on agricultural soils. In addition to chemical fertilizers, farmers also plow under the stubble from the previous year's crops, and they also commonly spread animal waste on fields. Accounting for these two sources approximately tripled the estimated amount of nitrogen placed on soils. In addition, following the IPCC recommendations, secondary emissions from nitrogen runoff into bodies of water were also counted.

The activity data vary in reliability. Estimates of the nitrogen content of chemical fertilizer consumption, based on U.S. Department of Agriculture and trade association statistics, are probably reasonably reliable. However, nitrogen fertilizer accounts for only about one-third of the nitrogen applied to agricultural soils. The balance is accounted for by animal manure and the plowing under of crop residues. The accounting of the volume and disposition of animal manure can be accurate only in a general way, because it is itself a calculated figure (number of animals times manure per animal times share spread on soils times nitrogen content of manure), in which all the variables (except animal populations) have only a moderate (25 percent or so) degree of certainty. The accounting worsens for agricultural residues, because this calculated figure (crop times residue ratio times nitrogen content times share not combusted) systematically undercounts failed crops, and the residue ratio and nitrogen contents can have only a moderate degree of certainty. Nonetheless, the actual nitrogen application to agricultural soils from all three sources, taken together, is probably within 50 percent of the actual (unobservable) figure.

The consequences of applying nitrogen to agricultural soils are far more problematic. Nitrous oxide emissions occur when a particular class of nitrous-oxide-emitting bacteria expand their ecological niche in agricultural soils. The bacteria compete with other, with non-emitting bacteria, and with plants to consume soil nitrogen. Thus, actual emissions from any particular plot of land will be determined by whether conditions are propitious, and they may range from nil to at least twice the national average emissions factor.[196]

Conditions can be "propitious" for bacterial action generally, or specifically for nitrous-oxide-emitting microbes. Propitious conditions include high soil temperatures, adequate moisture, and soil that is neither too acid nor too alkaline, not too compacted, etc. Nitrogen fertilizers can also be deployed in ways that are more or less prone to stimulate bacterial action. Both scientific understanding of the conditions that promote nitrous-oxide-emitting bacteria and suitably detailed knowledge about the conditions on American farmlands for the calculation of more detailed and accurate emissions factors are absent at present. Thus, whatever the state of the activity data, the emissions factors applied can only be considered accurate to plus or minus 100 percent.

Crop Residue Burning

The accuracy of emissions estimates for crop residue burning is limited, because the practice of burning crop residues in the United States has not been quantified. As described above in the discussion of methane emissions from crop residue burning, a default figure of 3 percent was used in the calculation.

Waste Combustion

Nitrous oxide emissions from waste combustion are estimated by multiplying the volume of waste combusted annually by an emissions factor for each ton

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[195] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual*, IPCC Guidelines for National Greenhouse Gas Inventory, Vol. 3 (Paris, France, 1994), pp. 4.94-4.110.

[196] The IPCC estimates the range for this emissions factor at 0.0025 to 0.0225 kilograms of N_2O-N per kilogram of nitrogen applied. Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.89, web site www.iea.org/ipcc/invs6.htm.

combusted. Data on waste combustion probably are accurate to within plus or minus 33 percent, but the emission factor may vary by an order of magnitude.

Human Sewage in Wastewater

Emissions from human sewage in wastewater are a function of U.S. population, per capita protein intake, and the conversion rate of nitrogen to nitrous oxide during wastewater treatment. Population and per capita protein intake have a very small error band, but the rate at which nitrogen is converted to nitrous oxide is highly uncertain. The conversion rate is altered by the presence or absence of oxygen, wastewater temperatures, and acidity. In the absence of other data, a global average emissions factor provided by the IPCC was applied.

Adipic Acid Production

For adipic acid production, emissions estimates are based on three data inputs: production activity, an emissions factor, and emissions abatement activity. The primary sources of uncertainty are the amount of production at plants with emissions abatement and the effectiveness of the abatement techniques in eliminating nitrous oxide. In addition, the emissions factor for adipic acid production was determined by stoichiometry. Because plant-specific production figures must be estimated by disaggregating total adipic acid production on the basis of existing plant capacities, any national estimate will be an imprecise figure if the conversion of nitric acid to adipic acid is less than 100 percent efficient.

Nitric Acid Production

The emissions factor for nitric acid production is also uncertain. It is drawn from measurements at a single DuPont plant, which indicate a range of emissions from 2 to 9 grams of nitrous oxide per kilogram of acid production. Because the midpoint of the range was used in the calculation, estimates may err by as much as 65 percent. Applying the emissions factor range to total production also adds uncertainty, because the emissions reported at the DuPont plant may not be representative of emissions at all nitric acid production plants.

Halocarbons and Other Gases

Emissions of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are drawn from the work of the EPA. In general, most of these compounds are manufactured chemicals, and the amounts produced and sold can be determined, despite the fact that actual production and sales are not reported to the U.S. Government. On the other hand, the flow from sales of manufactured chemicals to emissions from their use is based on model output, particularly for HFC-134a and other refrigerants.

There are also significant fugitive emissions of these compounds, including the formation of perfluoroethane and perfluoromethane from aluminum smelting, fugitive emissions of sulfur hexafluoride from magnesium smelting, and emissions of HFC-23 from the manufacture of HCFC-22. Estimates of emissions from these sources are based on activity data multiplied by emissions factors, and the uncertainty of the estimates is probably on the order of 30 to 50 percent.

Appendix D
Emissions Sources Excluded

Certain sources of greenhouse gas emissions are not included in the estimates presented in this report. The omissions have been made on the basis of lack of essential data, highly speculative estimation methods, or classification as "natural" sources.

Biofuel Combustion

The carbon found in biofuels is the result of atmospheric uptake. During the combustion of biofuels, there is an immediate release of the carbon in the form of carbon dioxide. Thus, as part of the natural carbon cycle, carbon is reabsorbed over time. Because they produce no net change in the overall carbon budget, such emissions are not included in this report. If the initial flux had been counted, 1997 carbon dioxide emissions estimates would have been approximately 66 million metric tons of carbon higher than reported in Chapter 2 (Table D1).

Emissions are estimated by multiplying Energy Information Administration (EIA) energy consumption data for biofuels by the applicable emissions factors. The EIA data for municipal solid waste include methane recovery from landfills, but since the methane is not used as a biofuel, it has been subtracted for these calculations. Carbon dioxide emissions factors for combustion of wood fuels and municipal solid waste are taken from the EIA report, *Electric Power Annual 1996*.[197] The emissions coefficient for alcohol fuels, 17.99 million metric tons of carbon per quadrillion Btu, was derived specifically for use in this report.

Overseas U.S. Military Oil Consumption

Domestic military energy consumption is incorporated into U.S. energy statistics; however, energy consumption for overseas operations is a more complex issue. The data can either be reported in the national energy statistics of the host country or included in U.S. export statistics if domestic oil is transported to ships and other facilities. In some circumstances, the oil consumption may go unreported.

Estimating, even roughly, the quantity of oil consumed for overseas military operations is an uncertain procedure. The Defense Fuel Supply Center reports that petroleum "sales" (i.e., transfers to military sources and operating units) for fiscal year 1997 totaled 101 million barrels.[198] Of that, approximately 72 percent was acquired domestically and is assumed to be included in U.S. statistics. A reasonable estimate of military oil consumption not reported elsewhere would, therefore, be 28 percent of total military consumption of jet fuel,

Table D1. Estimated U.S. Carbon Dioxide Emissions from Biofuels, 1990-1997
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997
Municipal Solid Waste	9.24	8.14	9.31	8.90	9.36	9.47	9.50	8.89
Alcohol Fuel	1.63	1.29	1.57	1.75	1.92	2.06	1.47	1.74
Wood and Wood Waste . .	57.48	57.62	60.32	58.58	59.53	59.27	61.46	55.09
Total	**68.34**	**67.05**	**71.20**	**69.23**	**70.82**	**70.81**	**72.42**	**65.72**

NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997).

Sources: Underlying energy data from Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years), Table 10.2. Emissions coefficients for municipal solid waste combustion and wood and wood waste from Energy Information Administration, *Electric Power Annual 1996*, DOE/EIA-0348(95) (Washington, DC, 1997), Table C3.

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[197] Energy Information Administration, *Electric Power Annual 1996*, Vol. 2, DOE/EIA-0348(96/2) (Washington, DC, December 1997), Table A3, p. 129.

[198] Defense Fuel Supply Center, *Fact Book 1997*, web site www.dfsc.dla.mil/main/publicati.htm (February 1998).

middle distillates, and residual oil.[199] By this method, excluded emissions for 1997 were estimated at 2.0 million metric tons of carbon (Table D2).

Forest Fires

Forest fires are known to create greenhouse gas fluxes within the atmosphere over extensive time periods. Specifically, forest fires produce carbon dioxide, methane, and nitrous oxide. Considering that carbon uptake occurs with subsequent regrowth (assumed to balance out the initial carbon flux), and because emissions from natural forest fires cannot be distinguished from those from human-induced fires, estimates from this source are not included in this report.

Unaccounted for Gas

In previous years, the EIA has included in its estimated emissions a category called “unmetered natural gas.” In those years, U.S. natural gas producers consistently reported selling about 3 percent more natural gas than U.S. consumers reported buying. In EIA natural gas statistics, this “missing” gas is described as “the balancing item” or “unaccounted for gas.” The balancing item can be viewed as the sum of leakage, measurement errors, data collection problems, and undetected over- and underreporting, as well as undetected nonreporting. Only a fraction of this amount can credibly be attributed to leakage from transmission systems. Evidence from the electric utility sector—where transmission companies report gas sales and electric utilities report gas purchases—suggests that there may be undercounting of natural gas consumption.

Estimates of carbon dioxide emissions from this source were included in previous reports, on the grounds that there was an element of systematic underreporting of consumption in the balancing item. In the past 2 years, however, the sign of the balancing item has changed, and reported consumption now exceeds reported production. This development reduces the credibility of the undercounting theory, and consequently this report no longer carries “unmetered natural gas” consumption as a source of emissions. It is possible, however, that there has been an element of undercounting of natural gas consumption before 1996, which may be on the order of 1 percent (3 million metric tons) of natural gas emissions.

Fermentation

During the fermentation process, complex organic compounds are decomposed through a variety of chemical reactions. The most common is the anaerobic conversion of sugar into carbon dioxide and alcohol. Fermentation does not create a net flux of emissions, however, because the carbon dioxide produced is of biological origin.

Enhanced Oil Recovery

Carbon dioxide is injected into petroleum reservoirs for the purpose of retrieving additional oil. Over time, the carbon dioxide seeps into the producing well, creating a mixture of oil, natural gas, and carbon dioxide. If the energy content is sufficiently high, the gaseous portion of this mix will probably be sent to a gas plant. If the energy content is low, the gas is likely to be vented or flared. At this time, there is no basis for the EIA to estimate the quantity of added carbon dioxide that is vented or flared. The annual amount of carbon dioxide used for enhanced oil recovery is probably on the order of 12 million metric tons,[200] and emissions would be some fraction of that figure.

Lead Smelting

Smelting of lead includes a stage in which limestone undergoes calcination. As described in Chapter 2, carbon dioxide is released as a byproduct of the calcination reaction. Emissions estimates cannot be calculated for this report because there are no known statistics regarding the amount of limestone used in

Table D2. Estimated Carbon Emissions from U.S. Military Operations Abroad, 1990-1997
(Million Metric Tons of Carbon)

Item	1990	1991	1992	1993	1994	1995	1996	1997
Energy Consumption (Quadrillion Btu) . . .	0.25	0.30	0.12	0.20	0.18	0.14	0.19	0.10
Carbon Emissions	4.88	5.89	2.27	3.83	3.53	2.81	3.62	2.00

Sources: Energy consumption from Defense Fuel Supply Center, *Fact Book* (various years). Data converted from fiscal years in source publication into calendar years by weighted average. Carbon emissions from EIA estimates presented in this appendix.

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[199] Gasoline is presumably acquired for motor vehicles and, typically, is accounted for in both domestic and foreign energy statistics.

[200] The U.S. Department of Commerce reports total sales of industrial carbon dioxide at approximately 17 million metric tons annually, while Freedonia Group, Inc., reports that approximately 5 million metric tons are used for purposes other than enhanced oil recovery.

lead smelting. The EIA is currently researching alternative data sources in an effort to include estimates of these emissions in future reports.

Abandoned Coal Mines

Measurements taken from 20 abandoned coal mines in 1994 showed a total of some 25,000 metric tons of methane emissions for that year.[201] Extrapolating from this small sample to a national-level emissions estimate requires assumptions about the total number of abandoned mines, their emissions profiles during operation, their current condition (flooded or not), and other variables. Past extrapolation efforts have led to national-level estimates of emissions from abandoned coal mines of about 280,000 metric tons annually. However, EPA's Atmospheric Pollution Prevention Division now believes that the total may be as high as 384,000 metric tons.

Methane Emissions from Industrial Wastewater

Industrial operations in the United States use immense quantities of fresh water. Many industries, particularly food processing industries, discharge wastewater containing large volumes of organic material. Some portion of the organic material may decompose anaerobically, particularly if the industrial facility deliberately uses anaerobic decomposition as a treatment strategy. However, estimating emissions from this source presents certain significant challenges, because there is no clear mechanism for determining accurately the following:

- Volume of wastewater discharged
- Volume of organic matter included in the wastewater
- Extent and type of industrial wastewater treatment
- Fate of untreated organic matter discharged into the environment.

Anecdotal evidence suggests that beer manufacturers produce large volumes of organic matter and cause it to decompose anaerobically so that they can recover methane for energy purposes. It is possible that methane emissions from industrial wastewater are, in fact, a large emissions source, but there is insufficient evidence currently available to make a plausible estimate.

Nitrous Oxide Emissions from Industrial Wastewater

Just as industrial wastewater may contain large volumes of organic matter, so, under certain circumstances, industrial wastewater may be a source of nitrogen, leading ultimately to nitrous oxide emissions. However, the problems associated with estimating methane emissions from industrial wastewater are even more difficult with respect to nitrous oxide emissions from industrial wastewater. The nitrogen content of industrial wastewater is more problematic, and the extent to which bacterial action converts the nitrogen into nitrous oxide (as opposed to molecular nitrogen or nitrogen oxides) is more uncertain.

Methane Emissions from Wetlands

Wetlands are a known source of methane. Environments low in oxygen, combined with abundant organic matter, are conducive to the creation of methane, and wetlands meet both criteria. Wetlands cover approximately 274 million acres of land in the United States and are a potentially important source of atmospheric methane.

The stock of natural wetlands in the United States has diminished considerably over the past two centuries, which should, in principle, have reduced methane emissions from wetlands (the EIA is not aware of research proving or disproving this principle). A recent study of wetland losses concluded that the United States had lost approximately 30 percent of its wetlands between colonial times and the mid-1980s. Almost all of the loss has occurred in the lower 48 States, which have lost 53 percent of their original wetlands.[202] Ten States—Arkansas, California, Connecticut, Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri, and Ohio—have lost 70 percent or more of their original wetland acreage. By the mid-1980s, a total of approximately 119 million acres had been lost from the original U.S. total.

An update of the wetlands study indicates that 654,000 acres were converted from wetlands to other uses between 1982 and 1987, and that an additional 431,000 acres were converted between 1987 and 1991.[203] Extrapolating from these data, it is estimated that wetlands in the United States are currently destroyed at

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[201] S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

[202] T. Dahl, U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands Losses in the United States: 1780's to 1980's* (Washington, DC, 1990).

[203] U.S. Department of Agriculture, Soil Conservation Service, *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands* (Washington, DC, not dated), p. 4.

a rate of approximately 86,000 acres per year. Wetlands, also known as swamps and marshes, have historically been drained or filled in for agriculture, land development, and mosquito control, although it is currently illegal to drain or fill a wetland without a permit from the U.S. Army Corps of Engineers. It is difficult to find information on the conversion of other land categories *to* wetlands. It is assumed that the number and extent of wetland creations is small enough to leave the above loss estimates essentially unchanged.

Estimates of global methane fluxes from wetlands suggest that methane emissions from temperate-zone wetlands are minimal—typically between 5 and 10 million metric tons of methane per year for worldwide temperate-zone wetlands (which include U.S. wetlands)—when compared with estimated global wetlands emissions of 110 million metric tons.[204] The U.S. share of all temperate-zone wetlands is about 57 percent, and temperate-zone wetlands lost during the 1980s accounted for about 0.5 percent of U.S. wetlands at the beginning of the period. Consequently, the reduction in natural methane emissions from wetlands lost might be on the order of 0.57 × 0.005 × 5 to 10 million metric tons of methane, or from 10,000 to 20,000 metric tons of methane annually over the decade.

Land Use Changes Affecting Methane and Nitrous Oxide

The scientific literature suggests that both grasslands and forest lands are weak natural sinks for methane and weak natural sources for nitrous oxide. Natural soils apparently serve as methane sinks: well-aerated soils contain a class of bacteria called "methanotrophs" that use methane as food and oxidize it into carbon dioxide. Experiments indicate that cultivation reduces methane uptake by soils and increases nitrous oxide emissions.

One report indicates that methane uptake in temperate evergreen and deciduous forests in the United States ranges from 0.19 to 3.17 milligrams (measured in carbon units) per square meter per day, equivalent to the uptake of 36.8 to 624.4 metric tons of methane per million acres per year. The range is larger for agricultural lands: 0.2 to 6.3 milligrams per square meter per day. Estimates for methane uptake resulting from the abandonment of farmland range from 0.6 to 6.1 milligrams per square meter per day. While all of these ranges are wide, the total amount of methane in question is less than 1 percent of methane emissions from anthropogenic sources.

Of all the greenhouse gases discussed in this report, the least amount of data is available for nitrous oxide. It is known that conversion of forests and grasslands to cropland accelerates nitrogen cycling and increases nitrous oxide emissions from the soil. It is not known with certainty by how much.[205] Some estimates have been made of the difference between fertilized and unfertilized soils. According to one study, unfertilized soils produce emissions of 0.25 to 0.35 milligrams (measured in nitrogen units) per square meter per day, while emissions from fertilized soils range from 0.6 to 1.65 milligrams per square meter per day.[206] Thus, abandoning fertilization should reduce nitrous oxide emissions by 0.35 to 1.3 milligrams per square meter per day—the equivalent of 86 to 321 metric tons of nitrous oxide per million acres per year.

Applying this figure to the 35 million acres of cropland idled between 1982 and 1992 implies a reduction in nitrous oxide emissions ranging from 3,010 to 11,235 metric tons annually. In principle, however, about three-quarters of the reduction in emissions from this source should be captured by reduced application of nitrogen fertilizers; thus, reporting emissions reductions using this method would result in significant double counting of units already included in the agriculture statistics in Chapter 4.

If such estimates are to be applied to emissions inventories, a problem of crediting the uptakes applies. Removing an acre of farmland from production in a particular year creates a *permanent* annual methane sink that will absorb small additional amounts of methane each year thereafter, or at least until the use of the land changes. The method that should be used to credit such permanent reductions to a particular year is not obvious.

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[204] See E. Matthews and I. Fung, "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics," *Global Biogeochemical Cycles*, Vol. 1, No. 1 (March 1987); and K. Bartlett and R.C. Harriss, "Review and Assessment of Methane Emissions from Wetlands," *Chemosphere*, Vol. 26, Nos. 1-4 (1993), p. 280.

[205] See A. Mosier, "Nitrous Oxide Emissions From Agricultural Soils," paper presented at RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control (Amersfoort, The Netherlands, February 3-5, 1993).

[206] A. Mosier and D. Schimel, "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide," *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

Appendix E

Emissions of Energy-Related Carbon Dioxide in the United States, 1949-1997

This appendix presents estimates of U.S. carbon dioxide emissions for the period 1949-1997. The data were developed originally at the request of the President's Council of Economic Advisors, for inclusion in a graphic that appeared in the 1997 *Economic Report of the President*.[207] U.S. energy data have undergone a number of shifts over the years, and the estimates can be divided into three periods:

- **1980-1997.** The emissions estimates for this period were developed using the methods and sources described in this report. The energy data on which the emissions estimates are based are from the Energy Information Administration (EIA) data series published in the *State Energy Data Report*.[208]
- **1960-1979.** Before 1980, the EIA did not maintain a detailed accounting of carbon sequestration due to nonfuel use of fossil fuels. Hence, the data for industrial sector petroleum use, particularly in the category "other petroleum," are not as reliable as those for subsequent years. The EIA has also not attempted to develop annual emissions coefficients for fuels in use before 1980, and the estimates do not reflect any changes in fuel quality. The energy data for this period are also drawn from the database of the *State Energy Data Report*.
- **1949-1959.** The EIA has made no attempt to distinguish between residential and commercial energy consumption for historical data earlier than 1960. To provide consistent estimates for this appendix, the combined data for residential and commercial energy consumption have been prorated by fuel according to the ratio of consumption in 1960. Composite sectoral petroleum emissions factors are used for this period, based on 1960-weighted petroleum products emissions. The energy data for this period are drawn from the *Annual Energy Review*.[209]

In future years, EIA hopes to be able to create annual emissions factors for electric utility coal for the period 1949-1979, to extend the estimates to cover U.S. territories and non-energy carbon dioxide, to estimate sequestration from nonfuel use in somewhat more detail for the period 1974-1979, and to use historical data on consumption of petroleum products by product and sector for the 1949-1959 period, rather than the 1960-based sectoral averages.

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[207] Council of Economic Advisors, *Economic Report of the President* (Washington DC, February 1998), p. 167.

[208] Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), pp. 21-26, web site www.eia.doe.gov/emeu/sep/states.html.

[209] Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), pp. 37, web site www.eia.doe.gov/emeu/aer/contents.html.

Table E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, 1949-1997

(Million Metric Tons of Carbon)

	Residential					Commercial				
Year	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	15.1	23.2	30.2	19.0	87.4	5.0	13.2	42.2	15.0	75.3
1950	17.8	27.6	29.9	20.2	95.4	5.9	15.7	41.7	15.9	79.2
1951	21.8	30.1	26.4	22.5	100.8	7.2	17.1	36.8	17.8	78.8
1952	23.9	30.8	24.0	24.0	102.8	7.9	17.5	33.5	19.0	77.9
1953	24.8	31.3	20.6	26.2	103.0	8.2	17.8	28.8	20.7	75.4
1954	27.8	33.5	17.9	27.5	106.7	9.2	19.0	25.0	21.7	74.9
1955	30.9	36.0	17.8	30.0	114.7	10.2	20.4	24.9	23.7	79.2
1956	34.1	37.6	16.6	32.4	120.7	11.2	21.3	23.1	25.6	81.3
1957	36.7	36.5	12.7	34.7	120.7	12.1	20.7	17.7	27.4	78.0
1958	40.2	39.1	12.4	35.3	127.0	13.2	22.2	17.3	27.9	80.6
1959	43.5	39.9	10.6	39.1	133.1	14.3	22.6	14.8	30.9	82.6
1960	46.2	43.8	10.6	42.3	142.9	15.2	24.9	14.5	33.4	88.0
1961	48.4	45.1	9.6	44.4	147.5	16.0	25.3	13.2	34.6	89.2
1962	51.8	47.1	9.2	47.4	155.5	18.0	25.9	13.0	37.0	93.9
1963	53.2	47.4	8.0	51.9	160.5	18.7	25.5	11.1	41.7	97.0
1964	56.1	45.7	7.1	55.9	164.9	20.3	25.2	9.5	44.5	99.6
1965	57.9	47.8	6.6	60.2	172.5	21.4	28.1	9.0	47.9	106.4
1966	61.3	47.5	6.3	66.6	181.7	24.0	29.1	9.1	52.9	115.1
1967	63.9	49.2	5.4	69.8	188.4	29.0	30.1	7.8	55.7	122.6
1968	65.9	51.6	4.9	79.0	201.5	30.7	30.6	7.0	61.7	130.0
1969	70.0	52.5	4.6	87.1	214.2	33.3	30.7	6.6	66.4	137.0
1970	71.3	52.8	4.0	95.9	224.0	35.3	31.4	5.5	72.5	144.7
1971	73.3	53.3	3.7	100.8	231.1	37.0	30.5	5.2	76.3	149.0
1972	75.7	55.5	2.9	109.0	243.1	38.5	30.9	4.0	83.6	156.9
1973	72.0	54.2	2.7	117.5	246.4	38.3	31.6	3.8	90.3	164.0
1974	70.5	49.4	2.7	114.6	237.1	37.6	28.7	3.8	87.2	157.4
1975	72.3	47.9	2.2	113.1	235.5	36.8	26.3	3.1	90.1	156.3
1976	74.1	52.3	2.1	119.4	247.9	39.1	29.4	3.0	96.8	168.4
1977	70.8	51.8	2.2	129.0	253.7	36.7	30.4	3.1	102.8	173.0
1978	71.8	50.4	2.2	130.8	255.2	38.0	29.1	3.3	103.2	173.6
1979	72.7	40.8	1.9	134.1	249.5	40.8	26.9	2.9	106.7	177.3
1980	69.9	33.6	1.6	143.3	248.4	38.4	26.1	2.2	111.6	178.3
1981	67.0	29.6	1.8	141.5	239.9	37.1	22.0	2.5	116.7	178.3
1982	68.4	27.6	1.9	139.6	237.6	38.5	20.3	2.9	116.5	178.2
1983	65.0	25.9	1.9	143.3	236.2	36.1	22.5	3.0	118.5	180.0
1984	67.5	25.6	2.1	146.0	241.2	37.3	23.8	3.2	124.4	188.8
1985	65.7	28.4	1.8	150.0	245.8	36.0	20.6	2.7	130.2	189.7
1986	63.8	27.9	1.8	150.6	244.1	34.3	21.9	2.7	131.5	190.5
1987	63.9	28.8	1.7	156.7	251.0	36.0	21.5	2.6	137.2	197.2
1988	68.5	29.9	1.7	164.8	264.9	39.5	20.7	2.6	144.9	207.6
1989	70.9	29.7	1.5	165.4	267.6	40.3	19.2	2.3	148.3	210.0
1990	65.1	24.0	1.6	162.5	253.1	38.8	18.0	2.4	147.5	206.8
1991	67.5	24.5	1.4	163.8	257.2	40.4	17.1	2.2	146.7	206.4
1992	69.4	24.9	1.5	160.2	256.0	41.5	16.1	2.2	145.6	205.5
1993	73.4	26.3	1.5	170.6	271.8	43.1	14.9	2.2	151.9	212.1
1994	71.7	25.4	1.4	169.8	268.4	42.9	14.9	2.1	153.9	213.9
1995	71.8	25.8	1.4	171.4	270.3	44.9	14.1	2.1	156.8	217.9
1996	77.5	27.3	1.4	179.4	285.6	46.7	14.6	2.1	162.5	226.0
1997	74.1	27.8	1.4	183.2	286.5	48.6	14.4	2.1	172.1	237.2

Sources: **1996-1997**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1995**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1980**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Table E2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, 1949-1997

(Million Metric Tons of Carbon)

	Industrial					Transportation				
Year	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total**	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total**
1949	45.9	57.7	131.6	33.1	268.4	1.9	119.1	42.9	0.5	164.5
1950	51.1	66.0	140.2	38.4	295.7	2.8	129.7	38.9	0.6	172.0
1951	58.3	70.5	149.9	42.6	321.2	3.1	142.7	34.2	0.6	180.6
1952	60.2	71.6	133.5	43.7	309.0	3.4	149.1	24.5	0.6	177.6
1953	61.9	73.5	143.6	49.1	328.1	3.4	156.1	18.2	0.6	178.4
1954	62.2	75.1	114.5	48.5	300.3	3.7	157.8	11.5	0.6	173.6
1955	67.7	82.9	136.0	60.5	347.0	4.5	169.9	10.5	0.7	185.5
1956	70.1	85.1	137.1	65.3	357.7	4.5	176.4	8.5	0.7	190.0
1957	73.6	84.0	133.8	65.4	356.8	4.6	179.8	6.0	0.7	191.2
1958	75.0	85.8	109.7	61.3	331.8	5.2	183.3	2.9	0.7	192.1
1959	81.3	90.3	106.8	67.4	346.0	5.2	190.6	2.2	0.8	198.7
1960	86.0	89.5	110.2	68.1	353.8	5.2	195.5	1.9	0.7	203.2
1961	86.9	89.1	105.3	69.7	350.9	5.6	199.3	0.5	0.7	206.1
1962	90.8	92.0	106.4	73.2	362.4	5.7	207.9	0.4	0.7	214.7
1963	95.2	93.5	111.3	78.1	378.2	6.3	215.5	0.4	0.6	222.8
1964	100.3	98.6	119.1	83.4	401.4	6.5	221.9	0.4	0.6	229.4
1965	103.5	102.1	124.0	88.8	418.3	7.5	228.9	0.4	0.6	237.3
1966	110.0	105.6	125.9	97.4	438.8	8.0	241.1	0.4	0.6	250.0
1967	113.6	105.5	119.4	99.6	438.0	8.5	253.1	0.3	0.6	262.5
1968	121.4	107.2	117.5	107.9	454.0	8.8	274.2	0.3	0.5	283.7
1969	129.8	111.3	113.4	114.1	468.6	9.3	285.7	0.2	0.5	295.8
1970	133.7	111.1	111.5	117.4	473.6	10.7	295.2	0.2	0.5	306.6
1971	138.7	111.3	94.8	119.0	463.8	11.0	307.0	0.1	0.5	318.6
1972	139.1	121.4	96.0	129.8	486.3	11.3	325.5	0.1	0.5	337.4
1973	147.2	128.4	97.7	139.2	512.5	10.7	343.8	0.1	0.5	355.1
1974	141.1	121.2	94.7	135.7	492.7	9.8	335.5	0.0	0.5	345.9
1975	120.7	114.6	88.9	132.3	456.4	8.6	339.6	0.0	0.6	348.8
1976	124.0	127.0	88.2	148.5	487.6	8.0	356.9	0.0	0.6	365.6
1977	122.3	137.8	83.7	157.2	501.0	7.8	371.3	0.0	0.6	379.7
1978	121.2	135.9	83.1	157.0	497.1	7.8	386.8	0.0	0.5	395.1
1979	120.9	143.6	88.3	165.4	518.1	8.8	383.2	0.0	0.6	392.7
1980	118.4	128.1	75.4	162.8	484.6	9.4	368.1	0.0	0.6	378.1
1981	116.3	109.9	75.8	161.7	463.7	9.5	364.0	0.0	0.6	374.1
1982	100.1	103.9	61.2	142.6	407.7	8.8	356.2	0.0	0.6	365.6
1983	95.2	96.0	60.2	148.1	399.4	7.3	359.0	0.0	0.6	366.9
1984	104.1	105.9	69.3	156.8	436.1	7.8	370.5	0.0	0.7	379.0
1985	98.9	100.1	67.8	158.0	424.7	7.5	376.1	0.0	0.7	384.4
1986	93.1	101.8	64.7	152.7	412.3	7.2	391.2	0.0	0.7	399.1
1987	101.8	101.2	66.1	158.1	427.2	7.7	402.7	0.0	0.7	411.1
1988	106.9	105.0	71.1	165.5	448.5	9.1	417.6	0.0	0.7	427.5
1989	112.8	99.2	69.4	169.1	450.5	9.4	422.6	0.0	0.7	432.7
1990	118.3	101.1	68.4	166.2	454.1	9.8	421.6	0.0	0.7	432.1
1991	120.2	95.4	64.8	162.3	442.7	8.9	414.9	0.0	0.7	424.5
1992	125.9	104.3	62.5	166.5	459.2	8.8	421.9	0.0	0.7	431.4
1993	131.3	98.3	62.1	167.6	459.2	9.3	426.8	0.0	0.7	436.7
1994	132.7	101.7	62.6	169.7	466.7	10.2	438.6	0.0	0.7	449.5
1995	140.2	96.0	62.3	166.5	465.0	10.4	447.4	0.0	0.6	458.5
1996	144.0	103.7	59.8	170.7	478.3	10.6	459.5	0.0	0.7	470.7
1997	142.2	105.8	58.5	176.5	482.9	10.5	461.9	0.0	0.7	473.1

Sources: **1996-1997**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1995**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1980**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Table E3. Energy-Related Carbon Dioxide Emissions from the Electricity Generation Sector, and Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, 1949-1997

(Million Metric Tons of Carbon)

	Electricity Generation Sector				End-Use Sectors				
Year	Natural Gas	Petroleum	Coal	Total	Residential	Commercial	Industrial	Transportation	Total
1949	8.2	8.7	50.7	67.6	87.4	75.3	268.4	164.5	595.6
1950	9.4	10.0	55.7	75.1	95.4	79.2	295.7	172.0	642.2
1951	11.4	8.5	63.6	83.5	100.8	78.8	321.2	180.6	681.5
1952	13.5	8.9	64.9	87.3	102.8	77.9	309.0	177.6	667.3
1953	15.4	10.8	70.4	96.7	103.0	75.4	328.1	178.4	684.9
1954	17.4	8.9	72.0	98.3	106.7	74.9	300.3	173.6	655.6
1955	17.1	10.0	87.7	114.8	114.7	79.2	347.0	185.5	726.3
1956	18.4	9.5	96.0	124.0	120.7	81.3	357.7	190.0	749.7
1957	19.9	10.6	97.8	128.3	120.7	78.0	356.8	191.2	746.6
1958	20.4	10.4	94.3	125.1	127.0	80.6	331.8	192.1	731.4
1959	24.3	11.7	102.1	138.1	133.1	82.6	346.0	198.7	760.3
1960	25.7	11.7	107.1	144.5	142.9	88.0	353.8	203.2	787.9
1961	27.2	11.8	110.3	149.4	147.5	89.2	350.9	206.1	793.7
1962	29.3	11.9	117.1	158.3	155.5	93.9	362.4	214.7	826.6
1963	32.0	12.4	127.9	172.3	160.5	97.0	378.2	222.8	858.6
1964	34.7	13.4	136.3	184.4	164.9	99.6	401.4	229.4	895.2
1965	34.7	15.3	147.5	197.4	172.5	106.4	418.3	237.3	934.5
1966	39.1	18.7	159.6	217.4	181.7	115.1	438.8	250.0	985.7
1967	41.1	21.4	163.2	225.7	188.4	122.6	438.0	262.5	1,011.5
1968	47.0	25.0	177.1	249.2	201.5	130.0	454.0	283.7	1,069.2
1969	52.0	33.3	182.8	268.1	214.2	137.0	468.6	295.8	1,115.6
1970	58.3	45.0	183.0	286.3	224.0	144.7	473.6	306.6	1,149.0
1971	58.9	52.9	184.8	296.6	231.1	149.0	463.8	318.6	1,162.5
1972	58.8	65.5	198.6	322.9	243.1	156.9	486.3	337.4	1,223.7
1973	53.8	74.4	219.3	347.5	246.4	164.0	512.5	355.1	1,277.9
1974	50.6	71.2	216.2	338.0	237.1	157.4	492.7	345.9	1,233.1
1975	46.5	67.0	222.6	336.1	235.5	156.3	456.4	348.8	1,197.0
1976	45.4	73.6	246.4	365.4	247.9	168.4	487.6	365.6	1,269.5
1977	47.3	82.6	259.8	389.6	253.7	173.0	501.0	379.7	1,307.4
1978	47.4	84.5	259.6	391.5	255.2	173.6	497.1	395.1	1,320.9
1979	51.9	69.6	285.3	406.9	249.5	177.3	518.1	392.7	1,337.7
1980	54.8	55.8	307.8	418.4	248.4	178.3	484.6	378.1	1,289.4
1981	54.1	46.7	319.7	420.5	239.9	178.3	463.7	374.1	1,256.0
1982	48.0	33.2	318.0	399.3	237.6	178.2	407.7	365.6	1,189.1
1983	43.1	32.7	334.6	410.4	236.2	180.0	399.4	366.9	1,182.5
1984	46.3	27.3	354.3	427.9	241.2	188.8	436.1	379.0	1,245.2
1985	45.5	23.1	370.3	439.0	245.8	189.7	424.7	384.4	1,244.6
1986	38.7	30.8	365.9	435.5	244.1	190.5	412.3	399.1	1,245.9
1987	42.2	26.7	383.7	452.7	251.0	197.2	427.2	411.1	1,286.6
1988	39.0	33.2	403.7	475.9	264.9	207.6	448.5	427.5	1,348.6
1989	41.2	35.7	406.5	483.5	267.6	210.0	450.5	432.7	1,360.8
1990	41.2	26.6	409.0	476.9	253.1	206.8	454.1	432.1	1,346.1
1991	41.1	25.1	407.3	473.5	257.2	206.4	442.7	424.5	1,330.8
1992	40.7	20.3	411.9	473.0	256.0	205.5	459.2	431.4	1,352.1
1993	39.5	22.5	428.6	490.7	271.8	212.1	459.2	436.7	1,379.8
1994	44.0	20.6	429.4	494.1	268.4	213.9	466.7	449.5	1,398.4
1995	46.8	14.0	434.4	495.3	270.3	217.9	465.0	458.5	1,411.7
1996	40.3	15.4	457.5	513.3	285.6	226.0	478.3	470.7	1,460.6
1997	43.8	17.6	471.0	532.4	286.5	237.2	482.9	473.1	1,479.6

Note: Emissions from electricity generation are prorated across the end-use sectors.

Sources: **1996-1997**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1995**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1980**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Appendix F

Common Conversion Factors

Permutations of SI Units

1 gC = 1 gram carbon (C)

1 GgC = gigagram carbon (C) = 1,000 metric tons carbon (C)

1 TgC = 1 teragram carbon (C) = 1 million metric tons carbon (C)

1 PgC = 1 petagram carbon (C) = 1 billion metric tons carbon (C)

1 ppmv = 1 part per million by volume in the atmosphere

1 ppbv = 1 part per billion by volume in the atmosphere

1 pptv = 1 part per trillion by volume in the atmosphere

Density

1 thousand cubic feet of methane = 42.28 pounds

1 thousand cubic feet carbon dioxide = 115.97 pounds

1 metric ton natural gas liquids = 11.6 barrels

1 metric ton unfinished oils = 7.46 barrels

1 metric ton alcohol = 7.94 barrels

1 metric ton liquefied petroleum gas = 11.6 barrels

1 metric ton aviation gasoline = 8.9 barrels

1 metric ton naphtha jet fuel = 8.27 barrels

1 metric ton kerosene jet fuel = 7.93 barrels

1 metric ton motor gasoline = 8.53 barrels

1 metric ton kerosene = 7.73 barrels

1 metric ton naphtha = 8.22 barrels

1 metric ton distillate = 7.46 barrels

1 metric ton residual oil = 6.66 barrels

1 metric ton lubricants = 7.06 barrels

1 metric ton bitumen = 6.06 barrels

1 metric ton waxes = 7.87 barrels

1 metric ton petroleum coke = 5.51 barrels

1 metric ton petrochemical feedstocks = 7.46 barrels

1 metric ton special naphtha = 8.53 barrels

1 metric ton miscellaneous products = 8.00 barrels

Alternative Measures of Greenhouse Gases

1 pound methane, measured in carbon units (CH_4-C) = 1.333 pounds methane, measured at full molecular weight (CH_4)

1 pound carbon dioxide, measured in carbon units (CO_2-C) = 3.6667 pounds carbon dioxide, measured at full molecular weight (CO_2)

1 pound carbon monoxide, measured in carbon units (CO-C) = 2.333 pounds carbon monoxide, measured at full molecular weight (CO)

1 pound nitrous oxide, measured in nitrogen units (N_2O-N) = 1.571 pounds nitrous oxide, measured at full molecular weight (N_2O)

Weight

1 kilogram = 2.205 pounds

1 short ton = 0.9072 metric tons

1 metric ton = 1.1023 short tons = 2,204.6 pounds

1 cubic meter = 35.3147 cubic feet

1 cubic centimeter = 3.531×10^{-5} cubic feet

Area

1 acre = 0.40468724 hectare (ha) = 4,047 m^2

1 hectare (ha) = 10,000 m^2 = 2.47 acres

1 kilometer = 0.6214 miles

Energy

1 joule = 947.9×10^{-21} quadrillion Btu

1 exajoule = 10^{18} joules = 0.9479 quadrillion Btu

1 quadrillion Btu = 1.0551 exajoule

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Glossary

Acid stabilization: A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

Aerobic bacteria: Microorganisms living, active, or occurring only in the presence of oxygen.

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Aerosols: Airborne particles.

Afforestation: Planting of new forests on lands that have not been recently forested.

Agglomeration: The clustering of disparate elements.

Airshed: An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

Albedo: The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See planetary albedo.

Anaerobes: Organisms that live and are active only in the absence of oxygen.

Anaerobic bacteria: Microorganisms living, active, or occurring only in the absence of oxygen.

Anaerobic decomposition: The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon: A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: A hard, black, lustrous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Often referred to as hard coal.

Anthropogenic: Human made. Usually used in the context of emissions that are produced as the result of human activities.

API Gravity: A scale expressing the density of petroleum products as established by the American Petroleum Institute.

Asphalt: A dark-brown to black cement-like material obtained by petroleum processing, containing bitumens as the predominant constituents. Includes crude asphalt as well as the following finished products: cements, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts.

Associated gas: Natural gas found mixed with crude oil in underground reservoirs, released as a byproduct of oil production.

Aviation gasoline: All special grades of gasoline for use in aviation reciprocating engines. Excludes blending components, which are blended or compounded into finished aviation gasoline.

Balancing item: A measurement of the difference between the reported amount of natural gas produced and the reported amount consumed.

Biofuels: Organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: Materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

Biosphere: The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Bituminous coal: A dense, black, soft coal, often with well-defined bands of bright and dull material. The most common coal, with moisture content usually less than 20 percent. Used for generating electricity, making coke, and space heating.

BOD_5: The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

Bromofluorocarbons (halons): Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

Bunker fuel: Fuel supplied to ships and aircraft in international transportation, irrespective of the flag of the carrier, consisting primarily of residual fuel oil for ships and distillate and jet fuel oils for aircraft.

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene's cement, in pigments, as a paper filler, and as a drying agent.

Calcium sulfite: A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

Capital stock: Property, plant and equipment used in the production, processing and distribution of energy resources.

Carbon black: An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon reservoirs (e.g., atmosphere and biosphere) in the carbon cycle.

Carbon cycle: All carbon reservoirs and exchanges of carbon from reservoir to reservoir by various chemical, physical, geological, and biological processes. Usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs, regions of the Earth in which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools, ranging in size from individual communities or ecosystems to the total of all living organisms (biota).

Carbon dioxide: A colorless, odorless, non-poisonous gas that is a normal part of the ambient air. Carbon dioxide is a product of fossil-fuel combustion. Although CO_2 does not directly impair human health, it is a greenhouse gas that traps the earth's heat and contributes to the potential for global warming.

Carbon dioxide equivalent: The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. Carbon dioxide equivalents are generally computed by multiplying the amount (in kilograms) of the gas of interest (for example, methane) by its estimated global warming potential. Some analysts (and this report) use "carbon equivalent units" for convenience, defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon flux: See carbon budget.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. Vegetation and soils are common carbon sinks.

Catalytic converter: A device containing a catalyst for converting automobile exhaust into mostly harmless products.

Cesspool: An underground reservoir for liquid waste, typically household sewage.

Chlorofluorocarbons (CFCs): A family of inert, nontoxic, easily liquefied chemicals used in refrigeration, air conditioning, packaging, and insulation, or as solvents or aerosol propellants.

Climate: The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

Clinker: Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700^{o}F.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: A hard, porous product made by baking bituminous coal in ovens at temperatures as high as 2,000^{o}F. Used both as a fuel and as a reducing agent in blast furnaces. The term "coal coke" is used instead of "coke" to distinguish it from petroleum coke.

Coalbed methane: Methane produced from coalbeds in the same way that natural gas is produced from other strata. See "methane."

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Cracking: The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The removal of forest stands.

Degasification system: The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon, present in such solid waste as paper, food waste, and yard waste, that is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Distillate fuel: A general classification for the petroleum fractions produced in conventional distillation operations. Included are products known as No. 1, No. 2, and No. 4 fuel oils and No. 1, No. 2, and No. 4 diesel fuels. Used primarily for space heating, on- and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation.

Efflux: An outward flow.

Electrical generating capacity: The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

EMCON Methane Generation Model: A model for estimating the production of methane from municipal solid waste landfills.

Emissions: Anthropogenic (human-caused) releases of greenhouse gases to the atmosphere (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient/factor: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per barrel of fossil fuel consumed).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Eructation: An act or instance of belching.

Ethyl tertiary butyl ether (ETBE): A colorless, flammable, oxygenated hydrocarbon blend stock.

Ethylene: An olefinic hydrocarbon recovered from refinery or petrochemical processes.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flange: A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

Flared natural gas: Natural gas burned in flares on the well site or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach of an animal.

Flue gas desulfurization: Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

Fluidized-bed combustion: A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Flux material: A substance used to promote fusion, e.g., of metals or minerals.

Fodder: Coarse food for domestic livestock.

Forestomach: See *rumen.*

Fossil fuel: Any naturally occurring organic fuel formed in the Earth's crust, such as petroleum, coal, or natural gas.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, and / or transportation of fossil fuels.

Gasification: A method for exploiting poor-quality coal and thin coal seams by burning the coal in place to produce combustible gas that can be collected and burned to generate power or processed into chemicals and fuels.

Gate station: Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

Geothermal: Pertaining to heat within the Earth.

Global warming potential (GWP): The instantaneous radiative forcing that results from the addition of 1 kilogram of a gas to the atmosphere, relative to that of 1 kilogram of carbon dioxide.

Greenhouse effect: A popular term used to describe the roles of water vapor, carbon dioxide, and other gases in keeping the Earth's surface warmer than it would otherwise be. These radiatively active gases are relatively transparent to incoming shortwave radiation, but are relatively opaque to outgoing longwave radiation. The latter radiation, which would otherwise escape to space, is trapped by greenhouse gases within the lower levels of the atmosphere. The subsequent re-radiation of some of the energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. There is concern that increasing concentrations of greenhouse gases, including carbon dioxide, methane, and chlorofluorocarbons, may enhance the greenhouse effect and cause global warming.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, tropospheric ozone, nitrous oxide, and methane, that are transparent to solar radiation but opaque to longwave radiation, thus preventing longwave radiation energy from leaving the atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross gas withdrawal: The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

Gypsum: The most common sulfate mineral. Used in wallboard.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine or bromine.

Halons: See bromofluorocarbons.

Heating degree-day: The number of degrees per day that the average daily temperature is below 65 degrees Fahrenheit.

Herbivore: A plant-eating animal.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydrochlorofluorocarbons (HCFCs): Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

Hydrofluorocarbons (HFCs): Chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms.

Hydroxyl radical (OH): An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

Jet fuel: Kerosene- and naphtha-type fuels for jet engines. Kerosene-type jet fuel is a kerosene-quality product used primarily for commercial turbojet and turboprop aircraft engines. Naphtha-type jet fuel is a fuel in the heavy naphtha range used primarily for military turbojet and turboprop aircraft engines.

Kerosene: A petroleum distillate that has a maximum distillation temperature of 401^{o}F at the 10-percent recovery point, a final boiling point of 572^{o}F, and a minimum flash point of 100^{o}F. Used in space heaters, cookstoves, and water heaters, and suitable for use as an illuminant when burned in wick lamps.

Ketone-alcohol (cyclohexanol): An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

Leachate: A liquid produced as water percolates through wastes, collecting contaminants.

Lignite: A brownish-black coal of low rank with high inherent moisture and volatile matter content, used almost exclusively for electric power generation. Also referred to as brown coal.

Liquefied petroleum gases (LPG): Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Lubricant: A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not include byproducts of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

Methane: A hydrocarbon gas (CH_4) that is the principal constituent of natural gas.

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: A light alcohol that can be used for gasoline blending. See oxygenate.

Methanotrophs: Bacteria that use methane as food and oxidize it into carbon dioxide.

Methyl chloroform (trichloroethane): An industrial chemical (CH_3CCl_3) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

Methyl tertiary butyl ether (MTBE): A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

Methylene chloride: A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

Motor gasoline: A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, obtained by blending appropriate refinery streams to form a fuel suitable for use in spark-ignition engines. Motor gasoline includes both leaded and unleaded grades of finished gasoline, blending components, and gasohol.

Multiple cropping: A system of growing several crops on the same field in one year.

Municipal solid waste: Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

Naphtha: A generic term applied to a petroleum fraction with an approximate boiling range between 122 and $400^{o}F$.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas liquids (NGLs): Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Natural gas, pipeline quality: A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide: A colorless gas, naturally occurring in the atmosphere, with the formula N_2O.

Nonmethane volatile organic compounds (NMVOCs): Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Octane: A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the antiknock properties of motor fuel.

Oil reservoir: An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen trapped within a geological formation and protected from evaporation by the overlying mineral strata.

Organic content: The share of a substance that is of animal or plant origin.

Organic waste: Waste material of animal or plant origin.

Oxidize: To chemically transform a substance by combining it with oxygen.

Oxygenate: A substance which, when added to gasoline, increases the amount of oxygen in that gasoline blend. Includes fuel ethanol, methanol, and methyl tertiary butyl ether (MTBE).

Ozone: A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

Ozone precursors: Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

Paraffinic hydrocarbons: Straight-chain hydrocarbon compounds with the general formula C_nH_{2n+2}.

Perfluorocarbons (PFCs): Chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a byproduct of aluminum smelting.

Perfluoromethane: A compound (CF_4) emitted as a byproduct of aluminum smelting.

Petrochemical feedstock: Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphthas (endpoint less than 401^{o}F) and other oils (endpoint equal to or greater than 401^{o}F).

Petroleum: Hydrocarbon mixtures, including crude oil, lease condensate, natural gas, products of natural gas processing plants, refined products, semifinished products, and blending materials.

Petroleum coke: A residue that is the final product of the condensation process in cracking.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

Pig iron: Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

Pipeline, distribution: A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

Pipeline, gathering: A pipeline that conveys gas from a production well/field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

Pipeline, transmission: A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Pneumatic device: A device moved or worked by air pressure.

Polystyrene: A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

Polyvinyl chloride (PVC): A polymer of vinyl chloride. Tasteless. odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Post-mining emissions: Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

Radiative forcing: The extent to which emitting a greenhouse gas into the atmosphere raises global average temperature.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Reforestation: Replanting of forests on lands that have recently been harvested.

Reformulated gasoline: Gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211K of the Clean Air Act.

Renewable energy: Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy.

Residual fuel oil: The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations and that conform to ASTM Specifications D396 and D975. Included are No. 5, a residual fuel oil of medium viscosity; Navy Special, for use in steam-powered vessels in government service and in shore power plants; and No. 6, which includes Bunker C fuel oil and is used for commercial and industrial heating, electricity generation, and to power ships. Imports of residual fuel oil include imported crude oil burned as fuel.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Sample: A set of measurements or outcomes selected from a given population.

Sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes, such as photosynthesis.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sinter: A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

Sodium silicate: A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fireproof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid gas, silicate of soda, sodium metasilicate, soluble glass, and water glass.

Sodium tripolyphosphate: A white powder used for water softening and as a food additive and texturizer.

Stabilization lagoon: A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

Still gas: Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

Stripper well: A well that produces 60 million cubic feet of gas per day or less for a period of three consecutive months while producing at its maximum flow rate.

Styrene: A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

Subbituminous coal: A dull, black coal of rank intermediate between lignite and bituminous coal.

Sulfur dioxide: A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Sulfur hexafluoride: A colorless gas soluble in alcohol and ether, slightly soluble in water. Used as a dielectric in electronics.

Sulfur oxides (SO_x): Compounds containing sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Tertiary amyl methyl ether (TAME): An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude. Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the Earth’s surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Uncertainty: A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

Vapor displacement: The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

Ventilation system: A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

Volatile organic compounds (VOCs): Organic compounds that participate in atmospheric photochemical reactions.

Volatile solids: A solid material that is readily decomposable at relatively low temperatures.

Waste flow: Quantity of a waste stream generated by an activity.

Wastewater: Water that has been used and contains dissolved or suspended waste materials.

Wastewater, domestic and commercial: Wastewater (sewage) produced by domestic and commercial establishments.

Wastewater, industrial: Wastewater produced by industrial processes.

Water vapor: Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

Waxes: Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

Weanling system: A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

Wellhead: The top of, or a structure built over, a well.

Wetlands: Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, and charcoal.

Yearling system: A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.